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Session III Proceedings

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Second-Best Pollution Taxes in
the Economics of Climate Change[*]

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ABSTRACT

Under first-best conditions, taxing greenhouse gas emissions at a rate equal to the discounted marginal cost that present emissions impose on future society would maximize the welfare gains generated by climate change mitigation measures. In this setting, the discount rate would be set equal to the marginal productivity of private capital. Based on a numerically calibrated model of the links between climate change and the world economy, this paper shows that using this so-called "first-best decision rule" may substantially understate the emissions tax rates that maximize welfare when the resulting revenues are used to reduce distortionary taxes on returns to capital. Using emissions tax revenues to reduce labor taxes, in contrast, results in an optimum with comparatively low welfare gains. In this case the first-best decision rule provides a good approximation of the second-best emissions tax. The lowest welfare gains and second-best emissions taxes emerge in the case where emission tax revenues are recycled through the use of lump-sum income transfers.

INTRODUCTION

Market-based incentives have emerged as important tools in environmental policy. While the environmental statutes of the 1970s emphasized "command-and-control" regulations and technology-based standards, the 1990 Clean Air Act amendments laid out a tradable permits scheme to achieve a 50% rollback in sulphur dioxide emissions from major stationary sources. More recently, economists have called for the use of greenhouse gas emissions taxes to address the threat of global climate change. In one early study, Pearce (1991) suggested that a greenhouse gas emissions tax might generate a so-called "double dividend," supporting both cost-effective emissions reductions and accompanying improvements in the efficiency of existing tax systems. Pearce's claim rests on the observation that an emissions tax of reasonable magnitude would raise quite substantial revenues.

The basic theory of environmental taxes was described in Pigou's seminal work *The Economics of Welfare* (1920) and was updated and extended by a later generation of environmental economists (Baumol and Oates, 1975). According to Pigou, pollution taxes serve to promote two key objectives. First, they provide incentives to balance the costs and benefits of polluting activities. Second, they ensure that the public is duly compensated for the harms caused by environmental externalities. In the Pigovian framework, the optimal tax rate is set equal to the marginal cost pollution imposes on society. This approach has found extensive applications in real-world policy analysis and plays a key role in the economics of climate change (IPCC, 2001).

The Pigovian model assumes a first-best world characterized by perfectly efficient markets and public policies. In real-world economies, however, existing taxes on labor and capital impose deadweight losses that impair the efficiency of resource allocation. Under second-best conditions, optimal emissions taxes may diverge from the marginal social cost imposed by

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pollution (Sandmo, 1975). This observation touched off an interesting debate on the fiscal impacts of environmental taxes.

On one side of this issue, Bovenberg and Goulder (1996; see also Parry *et al.*, 1999) cast doubt on the "double dividend" hypothesis. Bovenberg and Goulder analyze a model in which environmental taxes are introduced to an economy with pre-existing tax distortions. In this model, the second-best level for the environmental tax is generally lower than the marginal cost of pollution. Bovenberg and Goulder reason that environmental taxes exacerbate the distortions caused by income and payroll taxes. This cost implies that Pigou's rule for achieving first-best resource allocation may overstate optimal tax rates in the presence of pre-existing taxes.

An alternative perspective is offered by Shackleton *et al.* (1996), who employ a computable general equilibrium model to investigate the impacts of a greenhouse gas emissions tax on the U.S. economy. This model suggests that a moderate emissions tax would lead to net increases in economic growth and welfare if the revenues it generated were used to offset distortionary taxes on returns to capital. Such benefits would arise even in the absence of direct environmental benefits.

The purpose of this paper is to explore the connections between these seemingly divergent findings from the previous literature. In particular, the paper explores the second-best greenhouse gas emissions taxes that arise in a simplified model of climate change and the world economy that accounts for the influence of pre-existing taxation on markets for labor and capital. In the past, studies of second-best environmental taxes have focused mainly on static models that abstract away from issues of decision-making over time, while dynamic models that integrate the costs and benefits of greenhouse gas emissions abatement have generally abstracted away from issues of taxation and government expenditure.

The analysis concludes that a standard "first-best" decision rule tends to: (a) understate the optimal greenhouse gas emissions taxes that arise when the resulting revenues are used to reduce distortionary taxes on returns to capital; and (b) overstate the optimal emissions tax when revenues are recycled using lump-sum income transfers. Intermediate results occur when emissions tax revenues are used to reduce labor taxation. Under the first-best decision rule, the emissions tax is set equal to the discounted marginal cost that present emissions impose on future society, taking the marginal productivity of private capital as the appropriate discount rate.

THE MODEL

The analysis is patterned after Coleman's (2000) study of optimal tax policies in a competitive, intertemporal economy. Based on a set of empirical assumptions that pertain to the United States, Coleman developed a representative agent model of the interplay between households and producers in the presence of distortionary taxes. To link Coleman's framework to the economics of climate change, the present paper adopts this model in several respects. Most importantly, it revises the model's representation of technology and preferences to include the costs and benefits of greenhouse gas emissions and the accumulation of greenhouse gases in the atmosphere. In addition, it recalibrates the model based on a set of stylized facts that apply to the overall world economy. A full discussion of the model and its supporting assumptions is provided by Howarth (2003). For the present purposes, attention will be limited to a brief overview of the model's general structure.

Household Behavior

The household sector of the economy is represented by an infinitely-lived, representative agent that seeks to maximize the objective function:

$$V = \sum_{t=0}^{\infty} N_t u_t(c_t, l_t, S_t) 0.838^t \qquad (1)$$

under conditions of perfect foresight. In this specification, N_t is the population at date t,

measured in billions of persons; c_t is per capita consumption, measured in U.S. dollars at year

2000 prices; l_t is a measure of labor effort, defined as the proportion of non-sleep hours a typical

person spends at work; and S_t is the atmospheric stock of carbon dioxide, a greenhouse gas that

adversely affects global climate, measured in billion metric tons of carbon. Time is measured in

decades with the period $t = 0$ interpreted as the interval 2000-2009.

The utility function takes the form:

$$u_t = \ln(c_t) + 1.37 \ln(1 - l_t) + \ln\left(1 - 0.031(S_t - 590)/590\right). \qquad (2)$$

This specification gives rise to realistic levels of consumption, labor effort, and capital

investment. In addition, the parameters of the utility function imply that a doubling of the carbon

dioxide concentration relative to the pre-industrial level of 590 billion tons entails a welfare loss

that is equivalent to 3.1% of consumption. The specific damage coefficient is chosen based on

the IPCC's (1996, ch. 6) conclusion that a doubling might impose a cost equivalent to 1.75% of

economic output.

Based on data from the United Nations (2001), the model assumes that world population

grows from an initial value of $N_0 = 6.1$ billion persons according to the difference equation:

$$N_{t+1} = N_t + 0.31 N_t (1 - N_t / 10.9). \qquad (3)$$

This equation provides a good fit to observed population trends in the late 20th century, and

implies that global population achieves a long-run value of $N_\infty = 10.9$ billion.

Each member of the household holds the capital wealth k_t (measured in year 2000

dollars) and earns income by renting labor and capital services to the production sector at the

wage rate is w_t and the interest rate r_t. Governments tax the income earned on labor and capital at

the rates τ_{lt} and τ_{kt} while providing a transfer payment π_t to each individual. Under these conditions, the household faces the budget constraint:

$$c_t + k_{t+1} - k_t = (1 - \tau_{lt})w_t l_t + (1 - \tau_{kt})r_t k_t + \pi_t. \tag{4}$$

Taking prices, public policies, and the state of the environment as fixed at each point in time, a rational household would manage its decisions concerning consumption, labor effort, and net capital investment to maximize the objective function (V) subject to this budget constraint.

Producer Behavior

The production possibilities of the economy are determined by the prevailing capital stock ($K_t = N_t k_t$, measured in billion dollars), the labor supply ($L_t = N_t l_t$, measured in billion workers), and carbon dioxide emissions (E_t, measured in billion tons) according to the expression:

$$N_t c_t + G_t + K_{t+1} - K_t = A_t K_t^{0.4} L_t^{0.6} - 0.389 K_t - 486 E_{0t} \left(\frac{E_{0t} - E_t}{E_{0t}} \right)^{4.32}. \tag{5}$$

In this equation, net economic output is divided between consumption, government expenditure (G_t, measured in billion dollars), and net capital investment. A_t is a time-varying parameter that measures the level of total factor productivity, while $E_{0t} = B_t A_t K_t^{0.4} L_t^{0.6}$ is the level of carbon dioxide emissions that would occur in the absence of emissions control measures. Potential emissions are proportional to the level of gross economic output, with the parameter B_t interpreted as a time-varying coefficient that determines the emissions intensity of production.

In this economy, production is carried out by competitive firms that rent labor and capital from households at the wage rate w_t and the interest rate r_t. In addition, firms pay a tax τ_{Et} on each unit of greenhouse gas emissions. Given rational behavior, firms maximize their profits by

equating the marginal productivity of each factor of production with the prevailing price or emissions tax rate. Because the production function exhibits constant returns to scale, the value of output is just sufficient to cover the cost of purchased inputs. Hence profits are zero at each point in time.

As Howarth (2003) explains, this specification is based on plausible assumptions concerning the economic costs of carbon dioxide emissions abatement (IPCC, 2001; Weyant, 1999). In particular, emissions may be reduced by 20% relative to unconstrained levels at a marginal cost of $10 per ton. Given a 40% emissions abatement rate, the marginal cost of emissions control rises to $100 per ton. The model maintains Coleman's assumptions that: (a) labor and capital respectively account for 60% and 40% of the value of gross output; and (b) the capital stock depreciates at the rate of 4.8% per year.

The initial capital stock is $K_0 = 151,000$ billion dollars, while total factor productivity grows at an initial rate of 0.106 per decade from a starting value of $A_0 = 2473$. The growth rate falls linearly to a value of zero three centuries from the present. These assumptions were calibrated based on production statistics from the International Monetary Fund (2002).

Based on data from the IPCC (2000), the model assumes that carbon dioxide emissions would start out at 7.97 billion tons per year in the absence of control policies, which implies that the emissions-output coefficient assumes an initial value of $B_0 = 0.000179$. Since future technological progress will lead to declines in emissions intensity, the model assumes that B_t decreases at the rate of productivity growth. Although more detailed models represent emissions as an explicit function of land-use changes and the combustion of fossil fuels, the approach taken here provides a realistic time path for emissions when judged in comparison with the IPCC's (2000) comprehensive review.

The Global Atmosphere

The impacts of carbon dioxide emissions on future environmental conditions are represented using the functional form and parameter values adopted by Nordhaus (1994). In this specification, the atmospheric stock of carbon dioxide follows the recurrence relation:

$$S_{t+1} = 49.0 + 0.917 S_t + 0.64 E_t. \tag{6}$$

This equation is based on the assumptions that: (a) the natural or pre-industrial stock of carbon dioxide is 590 billion tons; and (b) excess levels of carbon dioxide are removed from the atmosphere at an annual rate of 0.86%.

Taxation and Government Expenditure

Completing the model requires a description of the approach that policy-makers take to choosing the various instruments that are under their control. To address this issue, the model assumes that governments maintain balanced budgets in each period, setting the value of public expenditure and transfer payments equal to the total revenues obtained through taxation so that:

$$G_t + N_t \pi_t = \tau_{lt} w_t L_t + \tau_{kt} r_t K_t + \tau_{Et} E_t. \tag{7}$$

Given a set of feasible public policies – i.e. a choice of the variables G_t, π_t, τ_{lt}, τ_{kt}, and τ_{Et} for each period of the model – the behavior of households and firms defines a competitive equilibrium for the world economy and its relationship to the global environment. While the model does not explicitly consider the social benefits provided by public expenditures, it is natural to suppose that government spending provides amenity benefits and/or augments private-sector productivity.

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CLIMATE CHANGE POLICY SCENARIOS

The purpose of this paper is to explore how environmental taxes interact with pre-existing taxes on capital and labor in the context of a dynamic model of the links between climate change and the world economy. In addressing this issue, it is useful to consider the welfare implications of five different policy regimes that differ in terms of their assumptions concerning emissions tax rates and the means through which governments return environmental tax revenues to the private sector. The details of each policy regimes may be described as follows.

Business-As-Usual

In the *business-as-usual* (BAU) scenario, governments tax labor income and returns to capital at the common rate $\tau_{lt} = \tau_{kt} = 1/3$. Half of the resulting revenues are used to finance public expenditures, while the remainder is returned to households in the form of transfer payments. While this setup does not correspond precisely to the tax policies of any one nation, data from the Organization for Economic Cooperation and Development (1998) suggest that the assumptions of this case are broadly representative of conditions in the world's advanced industrial nations, which dominate both global economic output and greenhouse gas emissions. In addition, these assumptions are numerically similar to those used in Coleman's (2000) analysis of U.S. fiscal policies. In the business-as-usual scenario there are no efforts to control greenhouse gas emissions. Hence the carbon dioxide emissions tax is set equal to zero at each point in time.

The "First-Best" Decision Rule

Under the *first-best decision rule*, policy-makers tax carbon dioxide emissions at a rate equal to the discounted marginal cost that present emissions impose on the future economy, interpreting the marginal productivity of capital – measured using the rental price of private capital (r_t) – as the appropriate discount rate. In formal terms, this approach yields the tax rate:

$$\tau_{Et} = \sum_{i=1}^{\infty} \left(MC_{t+i} \frac{\partial S_{t+i}}{\partial E_t} \prod_{j=1}^{i} \frac{1}{1+r_{t+j}} \right). \tag{8}$$

in which the expression:

$$MC_{t+i} = -N_{t+i} \frac{\partial u_{t+i} / \partial S_{t+i}}{\partial u_{t+i} / c_{t+i}} \tag{9}$$

represents the marginal cost that carbon dioxide imposes at date *t+i*, which depends on the prevailing population size and individuals' marginal willingness to pay to reduce carbon dioxide concentrations. The term $\partial S_{t+i} / \partial E_t$ captures the impacts of current emissions on future environmental quality.

In the absence of distortionary taxes on labor and capital, this decision rule would be sufficient to achieve a first-best outcome that maximized the perceived welfare of a representative household (Brekke and Howarth, 2003, ch. 7). In this scenario, policy-makers maintain public expenditures (G_t) at the levels that arise under business-as-usual, while releasing the revenues raised by the emissions tax through the use of lump-sum transfer payments (i.e, increases in the value of π_t).

Second-Best Emissions Taxes

In the remaining scenarios, the carbon dioxide emissions tax is chosen at each date to maximize the perceived welfare of a representative household (*V*) subject to the full set of

technical constraints and equilibrium conditions that characterize the economy's development over time. In these scenarios, the level of public expenditure is fixed according to the time path that prevails under business-as-usual. Since carbon dioxide emissions taxes raise revenues and since governments (by assumption) maintain balanced budgets, it is necessary to describe how governments release emissions tax revenues to the private sector. For the sake of analysis we focus three alternatives in which emissions tax revenues are used to provide:

1. Increased lump-sum transfers (π_t) – the *lump-sum recycling* scenario.

2. Reductions in labor tax rates (τ_{lt}) – the *labor tax recycling* scenario.

3. Reductions in capital tax rates (τ_{kt}) – the *capital tax recycling* scenario.

As we shall see, these various policy regimes differ importantly with respect to optimal emissions tax rates and the net benefits they provide to society.

RESULTS

The main results of this analysis are described in Figures 1-3. Under business-as-usual, carbon dioxide emissions rise from 8.0 to 24.8 billion tons over the course of the next century. Given this emissions path, the atmospheric stock of carbon dioxide rises to 1438 billion tons in the year 2100 – an increase of 144% relative to the pre-industrial norm.

The first-best decision rule supports a carbon dioxide emissions tax that rises from $25 per ton in 2000 to $183 per ton in 2100. The imposition of this tax restricts the level of emissions to 5.9 billion tons in the present and 12.8 billion tons in 2100 – figures that are (respectively) 26% and 48% below the levels that would prevail under business-as-usual. These emissions reductions give rise to a very substantial welfare gain. In comparison with business-as-usual, application of the first-best decision rule yields net benefits of $14.8 trillion. [This figure was

calculated by dividing the net increase in social welfare (V) by the marginal utility of consumption in the initial period.]

Of the various policy regimes considered in this analysis, the largest welfare gain arises in the capital tax recycling scenario. In this case, a comparatively low carbon dioxide emissions tax is prescribed in the initial period of the analysis. This result holds because the short-term capital stock is fixed according to past investment decisions, so reducing capital taxation in the immediate short run does not provide incentives for increased investment. In later periods, however, the emissions tax is substantially higher than the level prescribed by the first-best decision rule, rising to a full $280 per ton in the year 2100. In the capital tax recycling scenario, emissions are limited to a value of 6.4 billion tons in the present decade and 11.3 billion tons in the year 2100. In the context of the model, using the revenues raised by the emissions tax to reduce distortionary taxes on returns to capital generates quite substantial efficiency gains. In comparison with business-as-usual, the capital tax recycling scenarios generates total net benefits of $23.1 trillion.

The lump-sum recycling scenario, in contrast, performs relatively poorly. As Bovenberg and Goulder (1996) emphasize, the imposition of environmental taxes can exacerbate the inefficiencies imposed by pre-existing taxes under certain circumstances. In the scenario under discussion, this so-called "tax interaction" effect limits the second-best carbon dioxide emissions tax to $13 per ton in the present decade and $144 per ton in 2100. Over the course of the next century, carbon dioxide emissions rise from 6.2 to 13.6 billion tons, with a net welfare gain of $15.5 trillion.

Intermediate results occur in the labor tax recycling scenario. With the exception of the first period of the model – in which labor tax recycling supports a relatively high emissions tax – the carbon dioxide emissions tax rates and emissions levels that arise under this policy regime

are closely comparable to those prescribed by the first-best decision rule. Nonetheless, using emissions tax revenues to reduce distortionary taxes on labor income yields quite substantial economic benefits. Viewed as a whole, the labor tax recycling scenario yields net social benefits of $18.6 trillion – a figure that is $3.7 trillion higher than the level obtained under the first-best decision rule but $7.6 trillion below the net benefits provided by capital tax recycling.

Figure 1: Carbon Dioxide Emissions Tax
(U.S. dollars per ton, 2000 prices)
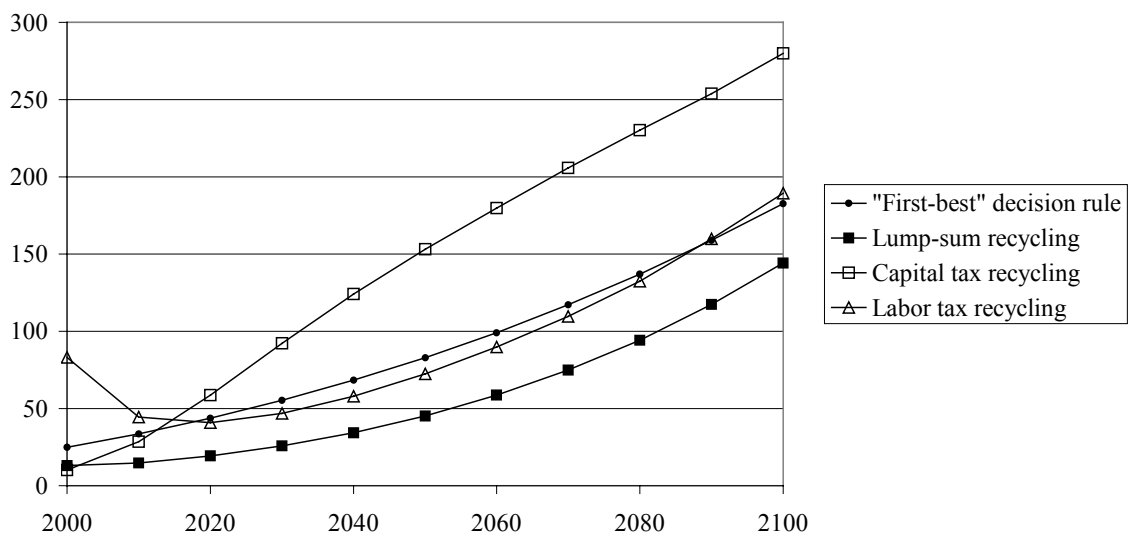
Figure 2: Carbon Dioxide Emissions
(billion tons per year)
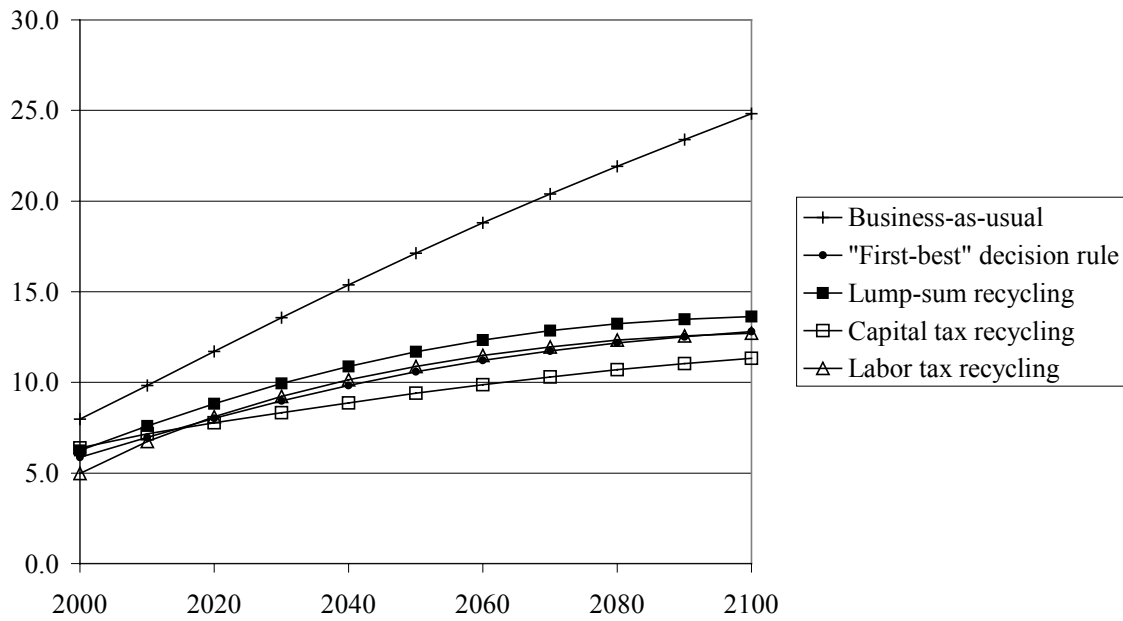
Figure 3: Welfare Gain Relative to BAU
(trillion U.S. dollars, 2000 prices)

CONCLUSION

The literature on market-based instruments for pollution control emphasizes that – under certain conditions – tax interaction effects provide a reason to impose second-best pollution taxes that are lower than standard measures of the marginal b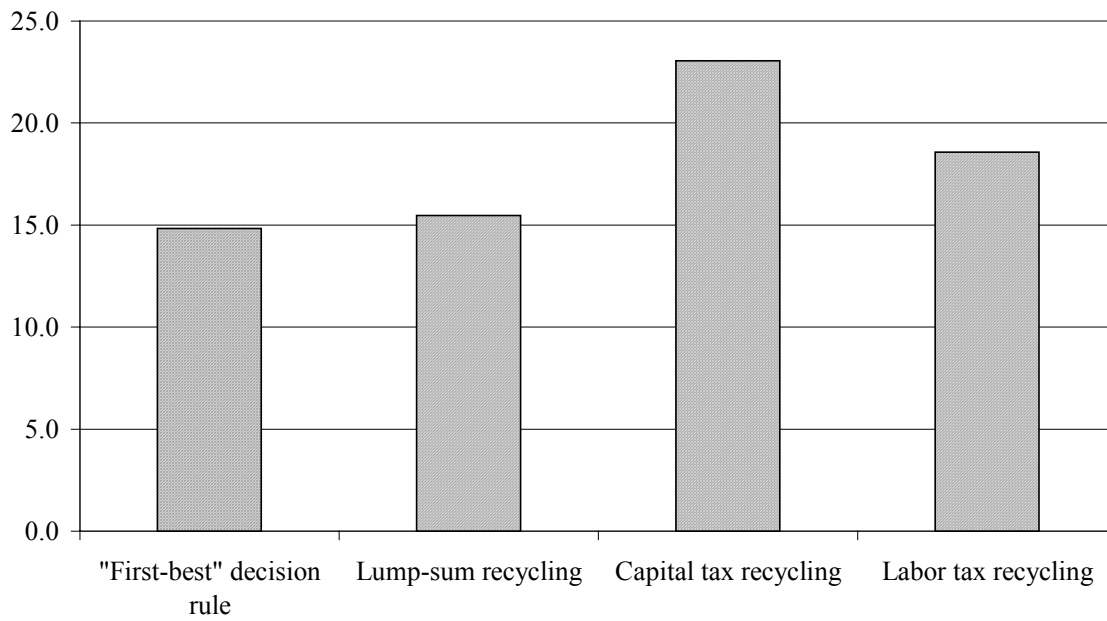enefits of pollution abatement (Bovenberg and Goulder, 1996). This result has been explored principally in the context of static models that abstract away from the impacts of taxation on capital investment and economic growth.

Building on the previous work of Shackleton *et al.* (1996) and Coleman (2000), the present study integrates the costs and benefits of greenhouse gas emissions abatement in the context of a dynamic model of climate change and the world economy. In this model, tax interaction effects support the imposition of relatively low emissions taxes when the resulting revenues are returned to the private sector in the form of lump-sum transfer payments. Mid-range emissions tax rates and net social benefits emerge when emissions tax revenues are used to reduce labor taxes.

Much larger welfare gains occur, however, when emissions tax revenues are used to reduce distortionary taxes on returns to capital investment. Given capital tax recycling, the optimal emissions tax is substantially higher than a standard (first-best) measure of the discounted marginal benefits of emissions control except in the immediate short run, when the capital stock is fixed so that reducing capital taxes does not alter incentives to invest.

These results rest on a highly simplified model that abstracts from many complexities of real-world economic and environmental systems. The analysis suggests, however, that the use of dynamic models can yield important insights regarding the links between fiscal policies and environmental taxation.

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Environmental Taxation Revisited

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ABSTRACT

This paper reexamines second-best environmental taxation at two levels. At the first level, the analysis compares the optimal environmental tax to marginal social damage ("the Pigouvian rate") using two alternative definitions of marginal social damage, one based on the social marginal rate of substitution between environmental quality and income, the other based on the sum of the private marginal rates of substitution. The comparisons are shown to lead to divergent inferences and predictions about the cost, benefits, and optimal levels of environmental policy in second-best settings with revenue-motivated taxes. At the second level of analysis, we test the validity of these alternative sets of predictions using numerical models for three types of externalities. The results are incompatible with claims made in the recent literature, but are consistent with the predictions that emerge when the social marginal rate of substitution is used to define marginal social damage: the optimal environmental tax is found to rise with an increase in the revenue requirements by identical amounts for all three types of externalities; the welfare changes are identical as well, as are the gains from "green tax reform." These results run counter to the claims in the recent "tax interaction" literature which predict large differences in the optimal environmental taxes and welfare changes between amenities versus income or productivity externalities. The discrepancies in these predictions are traced to the use of a definition of marginal environmental damage which does not reflect social valuations. Overall the analysis here concludes that environmental protection and the provision of other public goods are complementary rather than conflicting government goals.

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I. Introduction

A central task in environmental policy making is to appraise the costs and benefits of alternative policy goals and instruments. Among possible instruments, environmental taxes have long been favored by economists as mechanisms to internalize the external costs of pollution. This preference dates back to Arthur Pigou (1920; fourth edition 1932) who called for equating the value of the marginal social net product with the value of the marginal private product. He showed that a first-best "Pigouvian tax" set equal to the marginal social damage will fully internalizes the external costs of pollution.

In second-best economies where environmental taxes are considered alongside distortionary revenue-motivated taxes, Sandmo (1975) provides analytical results for optimal taxes which integrate revenue-raising and environmental objectives. His implicit expressions, however, do not provide transparent guidance for setting policy or for evaluating the welfare implications of specific policy changes.

Renewed interest over the past decade in environmental taxation has been due in part to attention to climate change and other environmental issues, and also to recent theoretical literature which has emphasized comparisons between the first-best Pigouvian tax and the optimal environmental tax in a second-best setting as a way to asses the effects of second-best settings on the benefits and costs of environmental policy (e.g., Bovenberg and de Mooij 1994; Parry 1995; Bovenberg and Goulder 1996).[1] Based on evaluations of whether the second-best optimal environmental tax will typically lie above or below the first-best Pigouvian tax, direct

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[1] See also Fullerton (1997), Bovenberg and de Mooij (1997), Goulder (1995), Parry, Williams and Goulder (1999).

inferences have been made in this literature about the costs and potential gains from environmental policy.

In general, the authors of these analyses found that the second-best optimal environmental tax typically lies *below* the Pigouvian rate, and from this they infer that the marginal cost of environmental policy must be rising with the marginal cost of public funds (Bovenberg and de Mooij 1994). They conclude further that the 'Pigouvian principle" must be modified in the presence of distortionary taxes in order to recognize that as public funds become more costly in a second-best setting "the government will find it optimal to cut down on public consumption of the environment by reducing the pollution tax" (Bovenberg and Goulder 1996). These conclusions also cast doubts on the potential for welfare-improving, revenue-neutral environmental tax reform: the authors conclude that "the gains from using pollution tax revenues to substitute for labor tax revenues tend to be more than offset by the cost of exacerbating the preexisting distortion in the labor market (Parry 1995). The authors ascribe these unexpected results to the existence of a previously unrecognized "tax interaction effect" (e.g., Goulder 1995; Fullerton 1997; Parry, Williams and Goulder 1999). These findings have also been used to judge the validity of the "double dividend hypothesis," which suggests that the revenue-neutral substitution of environmental taxes for revenue motivated taxes will produce two benefits, one related to the correction of the externality and the other related to improved efficiency of the tax system (see Tullock 1967, Pearce 1991, Terkla 1984, Lee and Miseolek 1986). Indeed, the finding that the optimal environmental tax is less than the Pigouvian rate has been put forward as evidence which "reveals how the intuition of the double dividend argument goes wrong" (Bovenberg and de Mooij, 1997).

More recently, several additional analyses involving externalities other than amenities have been evaluated in second-best settings such as those involving highway congestion, health,

or productivity. The results from these studies differ from those just summarized, indicating that the optimal environmental tax will be equal to the Pigouvian rate in the case of highway congestion and productivity (Parry and Bento 2001, Williams 2002), and possibility for health effects as well (Williams 2002). These authors attributed their results to previously-unrecognized "tax interaction effects," but in these cases they identify a "benefit-side tax interaction effect" which exactly offsets the adverse "tax interaction" distortions.

The current analysis reexamines optimal environmental taxation in first- and second-best settings for three types of externalities. As in recent literature, the optimal environmental tax is compared to the "Pigouvian rate" that fully internalizes the externality. We note, however, that two different definitions of the Pigouvian rate are possible, one based on the social marginal rate of substitution between the environment and income, and the other defined as the sum of private marginal rates of substitution. These two different expressions are found to be equal only at the first-best optimum, and this raises an unavoidable question of which measure will better serve as a benchmark, or yardstick, against which to compare the optimal environmental tax in second-best settings. In particular, we want to determine which of these measures can be compared to the optimal environmental tax as a way of making inferences and predictions about the costs and benefits of environmental policy.

In the analysis below, we find that when compared to marginal social damage (MSD, based on the social marginal rate of substitution), the second-best optimal environmental tax is generally higher than the Pigouvian rate, and rises with an increase in the revenue-requirement. The same relationship holds for all three kinds of externalities, and the results are consistent with the welfare changes which occur based on numerical simulation models for the U.S. economy where carbon taxes are introduced to address externalities from climate change.

By contrast, the sum of individual's marginal rates of substitution, or "marginal private damage" (MPD) is found to have no consistent relationship to either the second-best optimal environmental tax or marginal social damage across different types of externalities. Moreover, the evidence suggests that inferences about the welfare changes associated with environmental policy are not straightforward when based on the relationship between the optimal environmental tax and MPD. Large differences in the relationship between the optimal environmental tax and MPD across the three types of externalities are shown to occur even though the welfare changes are identical. Policy implications of these findings are discussed.

II. The first-best "Pigouvian tax"

Analytical derivations of the first-best Pigouvian tax can be found in many places in the literature. The aspects of these well-known derivations that we wish to highlight here can be seen transparently in a model with only one-good, where m identical households maximize utility by allocating an endowment of time, y, between leisure, l, and labor supply, y-l. In this stylized model, "full income" is taken to be the time endowment y, which households allocate between leisure and labor supply. In the second-best setting introduced below, a portion of this income is allocated to government to fund public goods. In ours and others' stylized models, revenues are simply returned lump sum to households.

Production is assumed to take place according to a linear production technology with only labor as an input. Output takes the form of a private consumption good, x, that creates an externality. Units are normalized so that private marginal rates of substitution

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between x and l are unity in the absence of a tax t on x, where the price $p=(1+t)$.

Environmental quality, E, is defined as $E = e(mx)$, $de/d(mx)<0$.

<u>Amenity externality</u>

In the case of an "amenity externality" the household's maximization problem can be

represented as

$$\underset{X,L}{\text{Max}}: \quad u(x,l,E)$$
$$s.t. \quad (\lambda) \quad (y-l)+g=(1+t)x \tag{1}$$

where households take government transfers, mg, and environmental quality, E, as given.

Let λ denote the Lagrange multiplier on the household budget constraint, reflecting the

private marginal utility of a unit of income.

We define our social optimization problem as one of choosing optimal taxes to maximize

social welfare, W, defined as the sum of individual utilities. For the amenity externality

case, the basic problem is:

$$\underset{t_x}{\text{MAX}}: \quad m\left[\begin{array}{l}\underset{X,L}{\max}:u(x,l,E)\\ s.t. \quad y-l+g=(1+t)x\end{array}\right]$$
$$s.t. \quad mg = mtx$$
$$E = e(mx)$$

$$\tag{2}$$

Taking the dual approach we can define the Pigouvian maximization problem in terms of the household's indirect utility function $v(p_x; y,E,g)=u(X^*(p_x;y,E,g), L^*(p_X;y,E,g))$, where the maximum value of u depends only on the taxes (implicit in p_x) and the parameters y, E and g.

We can express the social optimization problem with the Lagrangian equation involving households' utilities as well as constraints on revenues and environmental quality:

$$\text{Max:} \qquad = mv(p_x; y, E, g) + \mu(mt_x x - mg) + \phi(e(mx) - E).$$

(3)

These social constraints reflect limits of feasibility for the optimization problem which households are assumed to ignore, and represent essential elements which distinguish social valuations from private valuations.

We can derive the marginal social values for y and E using the Envelope Theorem which provides us with an expression for the rate of change of the maximum value of the objective function, where all variables adjust optimally in response to a change in a given parameter.

The social marginal utility of exogenous income, denoted by α, can be expressed as

$$\frac{\partial W}{\partial y} \equiv \alpha = \lambda + \mu\left(t\frac{\partial x}{\partial y}\right) + \phi e'\left(\frac{\partial x}{\partial y}\right). \tag{5}$$

where this expression includes the sum of gains from individual consumption, plus the gains from the marginal propensity to pay taxes out of income, plus the welfare change from the marginal propensity to pollute out of income. The first two of these terms were originally

recognized by Diamond (1985) in defining the social marginal utility of income (but in a model which did not consider externalities). The social marginal utility of income is used extensively in the optimal tax literature, for example in evaluating the optimal provision of public goods (see Auerbach 1985, p. 111).

The value of the Lagrangian multiplier ϕ can be interpreted as the social marginal utility of environmental quality: relaxing this constraint marginally, or exogenously adding one unit, would raise social welfare, W, by direct and indirect ways. We can write this as

$$\frac{\partial W}{\partial E} \equiv \phi = m\left[U_E + \mu\left(t\frac{\partial x}{\partial E} \right) + \phi e'\frac{\partial x}{\partial E} \right]. \tag{4}$$

Here we see that the social value of a unit increase in environmental quality has a direct value to households equal to mU_E, and also a social gain pertaining to the marginal change in tax payments when environmental quality increases. This second positive term is tempered by a third negative term owning to marginal changes in polluting activity in response to environmental improvement. For example, a decrease in air pollution may cause individuals to decrease their use of air conditioning, which further lowers pollution from the energy source.

In this first-best case with no distortionary revenue requirement, all revenues are returned lump-sum to households. As a result, an incremental change in g has the same effect on welfare as an incremental change in y. This implies that in this first-best case $\mu=\alpha$, the social marginal utility of income is equivalent to that for revenues.

The first-order condition for a representative household in our model is

$$- \lambda x + \alpha \left(t \frac{\partial x}{\partial p} + x \right) + \phi e' \frac{\partial x}{\partial p} = 0 \tag{6}$$

This can be rearranged to isolate t as

$$t = -\frac{\phi e'}{\alpha} + \frac{(\lambda x - \alpha x)}{\alpha \dfrac{\partial x}{\partial p}}.$$

By inspection we can see that if $\lambda = \alpha$ then the second term above drops out leaving $t = -\phi e'/\alpha$. Substituting this expression into the definition for α in (5) we find that, indeed, if $t = -\phi e'/\alpha$, that $\alpha = \lambda$. Substituting t* into (4), we see that the latter two terms cancel so that $\phi = mU_E$. We thus have two expressions for the first-best optimal environmental tax:

$$t* = -\frac{\phi e'}{\alpha} = \frac{mU_E}{\lambda}. \tag{7}$$

This result reflects the marginal rate of substitution between E and y, or "marginal social damage" (MSD), defined here as the welfare change from environmental damage (in utility units) divided by the social marginal utility of income. At the first-best optimum this expression of social values is equal to the private marginal rate of substitution summed across households (or ΣMRS), which we will refer to as "marginal private damages." The rule which equates benefits from a public good to ΣMRS has been referred to as the "conventional rule" (Atkinson and Stern 1974).

From Sandmo (1975) we can confirm that this result holds for the general case with n goods. Sandmo's expression for the optimal tax on a polluting good in a second-best setting can be rearranged and written using current notation as

$$t^* = \left(\frac{\mu - \lambda}{\mu}\right)R(1+t) - \frac{\phi e'}{\mu} \tag{8}$$

where $\boldsymbol{R}$ is the "Ramsey tax term." In the first-best case with no binding revenue-requirement, $\mu = \alpha$ and the Ramsey term on the right-hand side of (8) drops out so that the expression reduces to $t^* = -\phi e'/\alpha$.[2]

For completeness, the full expression for the first-best Pigouvian tax is

$$t^* = \frac{-\phi e'}{\alpha} = \frac{-m\left[U_E + \mu\left(t\frac{\partial x}{\partial E}\right) + \phi e'\left(\frac{\partial x}{\partial E}\right)\right]e'}{\lambda + \mu\left(t\frac{\partial x}{\partial y}\right) + \phi e'\left(\frac{\partial x}{\partial y}\right)} = \frac{-mU_E}{\lambda}e' \tag{9}$$

<u>Productivity externalities</u>

In the case of a productivity externality, our model involves labor productivity h=$h(E)$ so that the household maximization problem is

$$\begin{aligned}
\underset{X,L}{\text{Max}}: \quad & u(x,l) \\
\text{s.t.} \quad (\lambda) \quad & (y-l)h(E) + g = (1+t)x
\end{aligned} \tag{10}$$

And the social tax problem becomes:

$$\text{MAX :}_{t_x} \quad m \begin{bmatrix} \max_{x,l} : u(x,l) \\ s.t. \quad (y-l)h(E)+g = (1+t_x)x \end{bmatrix}$$
$$s.t. \quad mtx = mg$$
$$E = e(mx)$$

(11)

Following the same approach detailed above, and for simplicity taking yh to be a unit of income, we have

$$\frac{\partial W}{\partial(yh)} \equiv \alpha = \lambda + \mu \left(t \frac{\partial x}{\partial(yh)} \right) + \phi e' \left(\frac{\partial x}{\partial(yh)} \right)$$

(12)

$$\frac{\partial W}{\partial E} \equiv \phi = m \left[\lambda(y-l) + \mu \left(t \frac{\partial x}{\partial h} \right) + \phi e' \left(\frac{\partial x}{\partial h} \right) \right] h'.$$

(13)

As with the model above, we can substitute (18) and (19) into the first-order condition to obtain

$$t^* = \frac{-\phi e'}{\alpha} = \frac{-m \left[\lambda(y-l) + \mu \left(t \frac{\partial x}{\partial h} \right) + \phi e' \left(\frac{\partial x}{\partial h} \right) \right] h' e'}{\lambda + \mu \left(t \frac{\partial x}{\partial(yh)} \right) + \phi e' \left(\frac{\partial x}{\partial(yh)} \right)} = -m(y-l)h'e' \cdot$$

(14)

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[2] The expression derived by Bovenberg and Goulder (1996) for a second-best model using an income tax

where once again substituting t*=-φe'/α into both numerator and denominator sets the second and third terms in both numerator and denominator to have equal values and opposite signs, so that we can also write this as t*=-*m(y-l)h'e'*, which is just equal to the loss in output for the economy as a whole.

Income externalities

In this third type of externality referred to as an "income externality", our stylized model makes the underlying resource and source of full income, *y*, a function of environmental quality such that *y=y(E)*. The household maximization problem is

$$
\begin{aligned}
&\underset{X,L}{\text{Max}}: \quad u(x,l) \\
&\text{s.t.} \quad (\lambda) \quad (y(E)-l)+g = (1+t)x
\end{aligned}
\tag{15}
$$

And the social optimization problem becomes:

$$
\begin{aligned}
&\underset{t_x}{\text{MAX}}: \quad m\left[\begin{array}{l} \underset{X,L}{\max}: u(x,l) \\ \text{s.t.} \quad y(E)-l+g = (1+t\,)x \end{array}\right] \\
&\qquad \text{s.t.} \quad mtx = mg \\
&\qquad\qquad E = e(mx)
\end{aligned}
$$

$$
\tag{16}
$$

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normalization also reduces to this same expression in the first best case where α=μ and terms λ/λ can be cancelled.

Similar to the approach followed above, from the Envelope Theorem we have

$$\frac{\partial W}{\partial y} \equiv \alpha = \lambda + \mu\left(t\frac{\partial x}{\partial y}\right) + \phi e'\left(\frac{\partial x}{\partial y}\right)$$

(17)

$$\frac{\partial W}{\partial E} \equiv \phi = m\left[\lambda + \mu\left(t\frac{\partial x}{\partial y}\right) + \phi e'\left(\frac{\partial x}{\partial y}\right)\right]y' = m\alpha y'. \tag{18}$$

And the first-order condition gives us the optimal tax expression

$$t^* = -\phi e'/\alpha = -my'e'. \tag{19}$$

The sum of marginal private damages in this case is $(-m\lambda y'/\lambda)e'$ which can be simplified as -$my'e'$. Thus, for this third type of externality, both definitions of marginal damages, MSD and MPD will have the same value in the first-best setting.

To summarize, the Pigouvian rate which fully internalizes the marginal social damage from pollution can be expressed in two ways. First, it equals the social marginal rate of substitution between the environment and income. Intuitively this definition corresponds to Pigou's call for equating the value of the marginal social net product with the value of the marginal private product, since the cost of polluting is set equal to the social marginal utility of the environment, and converted into monetary units by divided by the social marginal utility of income. Second, at the first-best optimum the social marginal rate of substitution and the sum of private marginal rates of substitutions between the environment and income are equal, so that the

Pigouvian rate can also be expressed as "marginal private damages", summing the private marginal utility of the environment across households and using the private marginal utility of income.

When operating at the first-best optimum, either of these two expressions will do since they have the same value. In a second-best setting, however, they are not equal so that the question naturally arises; which of these expressions should be used as a benchmark for a) setting environmental policy and b) making predictions about the costs and benefits of environmental policy reforms?

III. Second-best optimal taxes

Before commenting on the question just posed, we want to derive expressions for the optimal environmental tax in a second-best setting in which government revenue-requirements involve distortionary taxes. For this we turn to a more general model with n goods, but maintaining the same general formulation as above for each of the three types of externalities. For each model some essential elements are presented here, others are presented in Appendix A. The resulting expressions for the optimal environmental tax follow closely those derived by Sandmo (1975).

It is well understood that when the financing of public goods requires distortionary taxes, the optimal provision of the public good will generally not follow the "conventional rule" which equates the ΣMRS to the marginal rate of transformation due to the added cost associated with the excess burden of raising revenues with distortionary taxes – but with the possibility of exceptional circumstances in which a positive income effect could offset this (Atkinson and Stern 1974)). This result holds when an increase in a given public good requires higher outflows

of public funds. In the case of environmental quality, however, more of the public good will coincide with a higher inflow of public funds from a pollution tax (unless demand is elastic). Given this difference between public goods where provision is correlated with positive government expenditures and those correlated with negative public expenditures, the effects of the cost of public funds on their provision may well go in opposite directions.

Before developing a set of analytical models and optimal tax expressions, it is useful to point out that some of the expressions found in the recent literature will differ in appearance from those in the prior optimal tax literature and the models presented below because they have normalized the tax program with an income (labor) tax rather than expenditure taxes for raising revenues. This leaves the untaxed good to be the non-polluting consumer good. Since an income tax will be equivalent to uniform taxes on all expenditures, it can serve as an optimal revenue raising tax if all goods are equal substitutes for leisure. However, this difference in normalization is understood have no effect on the actual outcomes of the optimization problem being addressed (Schöb 1996, Fullerton 1997).[3]

Amenity externality

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[3] Although the normalization of the tax rule does not affect any real variable, it can affect the relationship between the sum of marginal private damages and the social value of public goods (Atkinson and Stern 1974). In the current model with income (leisure) as the untaxed goods, an increase in tax rates does not affect units of income, either private or social. Thus the effects of a change in revenue requirements can be interpreted without also needing to account for changes in units. However, with the labor-tax normalization used in the recent literature where the untaxed good is non-polluting consumption, this consistency in units of income breaks down. An increase in revenue requirements raises the labor tax, which has the effect of altering the gross income (leisure) necessary to make possible consumption of one additional unit of the untaxed consumer good. As taxes rise, a unit of consumption stays the same from the household's perspective, but the autonomous income corresponding to that unit of consumption increases. In this formulation, the gross income (and its social value) corresponding to a unit of the clean good will necessarily rise with the revenue requirement, not because of a change in marginal social values but because the unit is growing proportionally with the labor tax. Thus, the numerical value of marginal social damage may decline with rising revenue requirements even if the utility function is linear. This is because the social unit of income is growing in size, so that fewer units will correspond to a value of MSD, even if the value would be constant if units were unchanged.

For the case of an amenity externality, the problem can be formulated as one in which m identical individuals maximize utility $U = u(x_0, x_1, x_2, ..., x_Z, ..., x_n, E)$ for goods $j = 0, ...,$ n, where leisure is x_0 and where labor supply is taken out of a time endowment, $y,$ so that labor supply equals y-x_0. Units are chosen for goods and income so that all pre-tax prices equal one, and where there are n-1 non-polluting x goods (excluding leisure) and one good x_z which produces an environmental externality. The consumption of x_z is assumed to erode the environment, E, where $E = e(mx_Z)$ and where $\dfrac{de}{d(mx_z)} < 0$.

In the amenity case, labor productivity, h, is constant, so that aggregate output is defined as $m(y$-$x_0)h = \Sigma mx_i$. Transfers of mg are financed by distortionary taxes, and E enters the utility function directly. Each household's maximization problem can be stated as

$$\begin{aligned} & \underset{x_0 \ldots x_n}{Max}: \quad u(x_0, x_1, \ldots x_n, E) \\[2mm] & s.t. \quad (y - x_0)h + g = \sum_{j=1}^{n}(1 + t_j)x_j \end{aligned}$$

The Lagrangian expression for each household taking E and G as given is thus

$$= u(x_0, x_1, \ldots x_n, E) + \lambda \left[(y - x_0)h + g - \sum_{j=1}(1 + t_j)x_j \right] \text{ for } j = 1, \ldots, z, \ldots, n. \quad (20)$$

Consumer prices are given as $p_j = 1 + t_j$ for $j = 1$ to n, but where income is untaxed, so that $p_0 = 1$.

The first-order conditions for each household take the form

$$U_j = \lambda(1 + t_j) \qquad\qquad\qquad j = 1, \ldots, n$$

$$U_o = \lambda h$$

$j=x_0.$

Our social optimization problem can be stated as

$$\underset{t_1 \dots t_n}{Max}: \quad m\left[u(x_0, x_1, \dots x_n, E) \quad s.t. \quad (y - y_0)h + g = \sum_{j=1}^{n}(1 + t_j)x_j\right]$$

$$s.t. \quad m\sum_{j=1}^{n} t_j x_j = mg$$

$$E = e(mx_z)$$

(21)

Taking the dual approach, we define the household's indirect utility function as $v(p_0, p_1, \dots p_n, y, g, E) = u(X_1*(p_0, p_1, \dots p_n, y, g, E), X_2*(p_0, p_1, \dots p_n, y, g, E), \dots X_n*(p_0, p_1, \dots p_n, y, g, E)),$ so we can state the social optimization problem as the Lagrangian equation

$$= mv(p_0, p_1, \dots p_n, y, g, E) + \mu\left[m\sum_{j=1}^{n} t_j x_j - mg\right] + \phi[e(mx_z) - E].$$

The first-order conditions are

$$-\lambda x_j + \mu\left[\sum_i t_i \frac{\partial x_i}{\partial p_j} + x_j\right] + \phi^a e' \frac{\partial x_z}{\partial p_j} = 0 \quad \forall \ j \neq 0.$$

(22)

from which the term involving environmental damage, denoted as $\phi^a e'$, is

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$$\phi^a e' = m\left[\frac{\partial U}{\partial E} + \mu \sum_i t_i \frac{\partial x_i}{\partial E} + \phi e' \frac{\partial x_Z}{\partial E}\right] e' \cdot$$

(23a)

For productivity and income externalities, respectively, the corresponding expressions for marginal social damage in utility units are:

$$\phi^p e' = m\left(\lambda(y - x_0) + \mu \sum_{i=1}^n t_i \frac{\partial x_i}{\partial h} + \phi e' \frac{\partial x_Z}{\partial h}\right) h' e'$$

(23p)

$$\phi^y e' = m\left(\lambda h + \mu \sum_{i=1}^n t_i \frac{\partial x_i}{\partial y} + \phi^y e' \frac{\partial x_Z}{\partial y}\right) y' e'$$

(23y)

From the expression in (22) we can see that the environmental component of the optimal tax will be a function of these expressions in utility units, φe', which includes the direct loss to households, the loss of revenues due to changes in consumption, and the indirect losses to households from the environmental consequences of changes in consumption of the polluting good. Unlike the first-best optimum, however, the second and third terms in this expression do not cancel, so that the optimal tax cannot be said to be a direct function of the sum of marginal private damages in utility units. The private costs of the tax correspond to the first term – the revenue raising value corresponds to the second term. Similarly the social marginal utility of income is no longer equal to the private marginal utility of income, but for the *n*-good model is,

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$$\alpha = \lambda + \mu \sum_{i=1}^{n} t_i \frac{\partial x_i}{\partial y} + \phi e' \frac{\partial x_z}{\partial y}$$

where the second and third terms are no longer of equal magnitude and opposite sign.

The optimal taxes are derived in Appendix A for each type of externality. From the first-order conditions we see that if the revenue recycling benefits of taxing pollution exceed the private costs at MSD, then the optimal tax can be expected to exceed MSD. This observation about the first-order conditions is similar for all three types of externalities, but without more information or restrictions on the model, the result is ambiguous.

If we place restrictions on preferences so that all goods are average substitutes for leisure (as has been done in some of the recent literature), we can rearrange the optimal tax expressions to isolate their environmental components. Defining τ^* as the differential between the optimal taxes on polluting and non-polluting goods, $(\tau^* = t_z - t_j)$, the optimal environmental tax for the amenity case, and for the other two types of externalities as well, can be written as

$$\tau^*_z = \frac{\alpha(1 + t_j)}{\mu}\left[\frac{-\phi e'}{\alpha}\right] \qquad (24)$$

The term in square brackets is MSD. We know that α/μ is less than one, and that $(1+t_j)$ is greater than one, so the question of whether τ^* is greater than or less than MSD is an empirical question, which will depends on preferences and tax levels which influence the parameters in (24). We evaluate this expression below using numerical general-equilibrium models. Values for these parameters commonly used in the literature, however, suggest that the optimal tax will generally exceed MSD.

As with the first-best case, some additional insight can be found by substituting the optimal tax (24) into the first-order conditions (22) and rearranging. Denoting the optimal revenue-raising tax on all goods as t_j^* (including x_z), and the environmental component of the tax on x_z as τ_z^* so that $t_z^* = t_j^* + \tau_z^*$, we can rearrange (22) and express it as

$$-\lambda x_j + \mu \left[\sum_i t_j^* \frac{\partial x_i}{\partial p_j} + x_j \right] - t_j^* \phi e' \frac{\partial x_z}{\partial p_j} = 0 \quad \forall \ j \neq 0 \tag{25}$$

At the optimum, a portion of the optimal environmental tax offsets the third-term in (22), the environmental consequences of dp_j. A portion of the optimal environmental tax expression remains, however, which is positive for all goods except x_z (e' being negative). This added welfare gain, at the optimum, is an increasing function of the optimal revenue-raising tax, and also an increasing function of marginal environmental damages (in utility units). It reflects how raising the tax on other goods will reap additional revenues from the pollution tax, aside from those necessary to offset any added environmental damage. In the case of x_z this term in negative because raising the tax on x_z discourages payment of additional pollution taxes (but we cannot determine from this that the optimal environmental tax is less than MSD). For the tax system overall, this term reflects a complementarity between government's revenue-raising objectives and environmental protection.

IV. Numerical model

The analytical expressions derived above give rise to predictions about the benefits and costs of environmental policy which differ from those found in the recent literature. Indeed, the present results would appear to support the existence of a "revenue-recycling" effect, but provide no evidence of negative or positive tax interaction effects: the optimal tax expressions derived above do not differ across types of externalities. To test these alternative predictions and the explanations which underlie them, we can employ some simple numerical models to confirm or refute the predictions of these two competing analyses with their differing conclusions about the changes in environmental taxes and welfare gains or losses when revenue requirements exceed those made available with a first-best Pigouvian tax.

As Sandmo pointed out (1975), when government needs to finance public goods, the revenues made available by a Pigouvian tax should be used first, since they represent a non-distorting source of public funds. If government were to return these revenues to the economy lump-sum, while at the same time introduce distortionary taxes to raise an equal or larger amount of revenues, this would clearly be a more distorting tax system than one that used the Pigouvian revenues to satisfy part or all of its revenue requirements. This aspect of the complementarity between environmental taxes and revenue-motivated taxes is not in dispute. It can be interpreted as one component of the "double dividend" (Bovenberg and de Mooij 1994).

Once these first-best Pigouvian revenues have been used up, however, additional revenues will require distortionary taxes and it is here that the issue of a "tax interaction effect" emerges. From a first-best starting point, a rise in revenue requirements above those made possible by the Pigouvian tax should lead to a reduction in the optimal environmental tax for an amenity externality according to the recent literature. In the case

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of an income or productivity externality, however, the optimal environmental tax will remain equal to marginal damages because of a benefit-side tax interaction effect which exactly offsets the cost-side tax interaction effect. Because of the presence of one or both of these tax interaction effects, large differences in welfare changes are expected between the amenity externality (with its cost-side tax interaction effect) and either the income or productivity externalities (with their benefit-side tax interaction effects). Moreover, starting from a second-best setting which ignores externalities, we expect that revenue-neutral environmental tax reform will produce much lower benefits for the amenity case than for the other cases.

Here we employ a general-equilibrium model that characterizes carbon emissions and climate change damages for the US economy based on data from 1995. The model is similar to one used in Parry, Williams and Goulder (1999), a version of which was also employed in Jaeger (2002). In the current context we utilize three versions of the model, one for each of the three types of externalities identified above. In each case, the model is calibrated so that the first-best optimum is the same for all three models. This gives our analysis a common starting point, one where MSD and MPD have the same value, and where both expressions are also equal to the Pigouvian tax. Given this common reference point for these nearly-identical models, we can perform several straightforward experiments to evaluate how the introduction of distortionary taxes affects the optimal environmental tax, and its relationship to MSD and MPD, as revenue requirements are raised to levels comparable to those in the U.S. economy.

A. Model specification

The model involves constant elasticity of substitution functions for utility and production, and is represented as a single period model rather than as a dynamic optimization problem. The model has m identical households who allocate their time between leisure (l) and labor supply (y-l). Utility is a function of consumption $u=U(x, l)$ and leisure. Consumer goods are produced with two intermediate inputs, one using fossil fuels (f), and one using non-carbon inputs (n), such that $x = X(f, n)$. We can therefore write utility as $u= U(x, (y$-$l))$. Production is assumed to be competitive, and labor is the only input used to produce the intermediate inputs f and n.

The preset model's structure has a more aggregated representation of production than the model used in Parry, Williams and Goulder (1999). Additional details of the model's structure and specification are presented in Appendix B.[4] Nested optimization models like our social planner's problem in (21) can be represented numerically as a single maximization problem by introducing the household's first-order conditions as constraints on social maximization. Setting $m=1$, and letting subscripts denote partial derivatives with respect to variable j (e.g., U_j and X_j), we write the social welfare maximization problem as

$$\underset{t_F, t_N}{\text{Max}}: \quad m\left[\mathrm{u}(x(f,n),l,E)\right]$$

$$
\begin{aligned}
s.t. \quad (\alpha) \quad & (1+t_f)f + (1+t_x)n = (y-l)h + G \\
(\mu) \quad & t_f f + t_n n = G \\
(\eta_1) \quad & U_x X_f (1+t_n) = U_x X_n (1+t_f) \\
(\eta_2) \quad & U_l (1+t_f) = U_x X_f h \\
(\phi) \quad & E = \pi f
\end{aligned}
\tag{26}
$$

In this model, the shadow value of the Lagrange multiplier on income, α, will reflect the social value of a unit of income because all optima in this model represent Pareto efficient states. Indeed, the private marginal utility of income, λ, does not appear directly in the model because it does not correspond to the Pareto efficient use of a marginal change in income. Rather, λ represents the value of a unit of income to households when taxes, E and G are held constant. If an incremental unit of income results in increased revenues or a change in environmental quality, the value of these changes is omitted when evaluating λ. Because of that, the private marginal utility of income will be less than the social marginal utility of income in an amount that reflects the marginal propensity to pay taxes. From society's perspective, one can also think of λ as reflecting a movement from a Pareto efficient state to a non-Pareto efficient state (with surplus, or deficit, revenues). That is, to the extent that a unit increase in income causes an increase in tax payments (assuming a positive marginal propensity to pay taxes), the value of λ does not afford any value to these added tax receipts. To evaluate λ at a particular optimum, we can fix t_n, t_f, G and E. The shadow prices on the income constraint will then reflect the private marginal utility of income since households take these parameters as given.

The three specifications being evaluated differ in that E enters the utility function only for the amenity externality. For the productivity externality h is a function $h(E)$, and for the income externality y is a function $y(E)$. Additional details are found in Appendix B.

B. Predictions

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[4] See Parry, Williams and Goulder (1999) for details of the source data and original calibration.

The tax interaction literature contains several central predictions about what happens as revenue requirements rise above those satisfied by a first-best Pigouvian tax for the three cases under investigation. In the case of the amenity externality, the tax interaction results suggest that the optimal environmental tax will decline below its first-best level (Bovenberg and de Mooij 1994, Bovenberg and Goulder 1996, Fullerton 1997). If utility and environmental damages are (approximately) linear over the relevant range (so that marginal damages are unchanged), we should expect that the optimal environmental tax will decline in dollar terms as revenue requirements increase. This prediction is said to be due to the presence of an additional distortionary cost, or "tax interaction effect" that lowers overall welfare.

The income externality case is similar to congestion pricing or health effects where an amount of endowed "time" is simply lost. The recent literature suggests that the adverse tax interaction effect is offset by "benefit-side tax interactions." In the congestion case, Parry and Bento (2002) find that the two effects are exactly offsetting, so that the optimal tax remains equal to the Pigouvian rate. In the health example, Williams (2002, p. 269) finds that the sign of this "benefit-side" tax interaction effect is ambiguous if medical expenses are involved, but that it will be positive if medical expenses are dominated by "time lost to illness." The present model does not consider medical expenses.

For the productivity externality case, Williams (2002) concludes that the optimal tax will equal the Pigouvian rate, because the two distinct tax interaction effects exactly offset each other. Thus, we expect no change in the optimal environmental tax if utility and environmental damages are approximately linear over the relevant range.

For these three models, then, as revenue requirements are raised, the tax interaction findings predict welfare to be higher for the productivity and income externalities, but

substantially lower in the case of the amenity externality. Given the common starting

point, the optimal environmental tax will also be higher for the productivity and income

externality cases than for the amenity case.

 One additional hypothesis can be tested with these simulations if we begin at a second-

best starting point with equal taxes on all goods, and simulate revenue-neutral

environmental tax reform which achieves optimality. The tax interaction literature

predicts that the welfare gains for the productivity and income externalities will be

significantly larger than for the amenity case.[5]

By contrast, the analysis above which relies on marginal social damage as a benchmark

leads to quite different hypotheses. Based on comparisons between the optimal

environmental tax and MSD, we expect that for all three externality types the optimal tax

will rise and that the welfare changes will be similar. We further expect that the gains

from environmental tax reform will be similar for all three models, and that those welfare

gains will exceed the gains for the revenue-neutral introduction of an environmental tax

equal to MSD.

C. Results

 Beginning at a common first-best starting point, where the optimal tax equals MSD and

MPD, we increase the revenue requirement above the levels that can be satisfied with the

corrective tax alone. This is done for three levels, the highest level ($2 trillion) being

comparable to revenue requirements and tax rates in the U.S. economy.

For each increase in revenue requirements, the optimal environmental tax rises above its first-best level for all three types of externalities, and the magnitude of the tax increase is essentially the same for all three as well (see Table 1). Beginning at a first-best tax of $25.4, the environmental component of the optimal tax rises to as high as $38 dollars per ton of carbon, or by 11%, 23%, and 50% for revenue requirements of $500 billion, $1 trillion, and $2 trillion, respectively. These environmental components are in addition to the revenue-raising taxes on both f and n, of 0.13, 0.28, and 0.61 percent, respectively. The results for the productivity externality case are consistent with those in Jaeger (2002).

We can interpret these comparisons as being between a non-distorting lump-sum tax (for each revenue requirement, but where revenues are simply returned lump-sum as well), and a distortionary tax program to collect the same revenues. If revenues are collected and returned lump-sum, the outcome is the same as the first-best case. From this perspective we can also see that the shift from non-distorting to distorting taxation has a very small effect on MSD (due only to the non-linearities in utility), whereas in the case of MPD, the value of MPD makes a significant jump by about 1/3rd of its value when the tax program changes from non-distorting to distorting at levels similar to those in the US economy. Interpreting the effect of distortionary taxes on the relationship between $\tau*$ and MPD when the value of MPD makes such a discrete shift is a manifestation of going from using a numeraire which includes the value of a full unit of income to one which includes only a portion of the value of a unit of income.

We can confirm that utility and environmental damages are approximately linear across these tax levels for the current models. Neither varies by more than three percent across

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[5] This change is predicted in concert with differences in the optimal environmental tax, of which evidence

tax levels for all types of externalities. A slight decline in MSD occurs over these tax scenarios for the amenity case (by 1.5%) owing to a slight rise in α due to the negative effect of the distortionary tax on utility. In the case of the productivity externality, there is a slight increase in MSD across tax scenarios (1%), owing to a slightly greater rise in ϕ compared to the increase in α. Given that the marginal values in both the utility function and production function vary only negligibly, these results are consistent with the expectation associated with the "double dividend hypothesis" that second-best optimal environmental taxes will exceed their first best levels.

The welfare changes from the first-best starting point for these second-best situations are also similar, declining to -$77 billion for the $2 trillion tax level. The welfare changes are negative because distortionary taxes have been introduced but without an explicit public sector or public good which would justify these taxes; the revenues are simply returned lump sum to households.[6]

The results for environmental tax reform at the $2 trillion revenue level indicate similar welfare gains for each type of externality, and the optimal environmental tax ends up being the same across all three externalities (Table 1). The gains differ slightly for the income and productivity externalities compared to the amenity case, but this is due to the small non-linearities in their environmental damage functions that give rise, at this level of revenue requirements, to slight differences in MSD. The differences in welfare gain from environmental tax reform are proportional to the differences in MDS.

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to the contrary has already been noted.
[6] A public good could be introduced separably into the utility function and calibrated to give rise to its optimal provision at each of the three levels indicated. In that case we would see equal welfare gains across all three types of externalities.

These results lead to the rejection of the predictions coming from the tax interaction literature: the optimal environmental tax does not decline for the amenity case, and the welfare changes do not differ significantly across types of externalities. The results are, however, consistent with the predictions made when using MSD as a benchmark measure of social valuations. Relative to MSD, the optimal tax rises about 50 percent at the G=$2 trillion level. Welfare changes are invariant across types of externalities. Beginning with equal taxes for both goods, the optimum occurs with an environmental tax about 50 percent higher than MSD, indicating that the welfare gain is higher than it would have been had tax reform been halted at the Pigouvian rate, t*=MSD. This result supports the inference of the double dividend, and the result is invariant across types of externalities. The origins of the claims about tax interaction effects in the recent literature can be traced to the use of MPD as the benchmark for comparing to the optimal environmental tax. But in models like the ones used here where marginal utilities are approximately constant over the relevant range, that with a measure like MPD which values a unit of income as λ, that this value declines by 1/3rd between the first-best case and the $2 trillion second-best case, even though consumption remains unchanged (the sum of f, n, and l is exactly the same for all scenarios since revenues are returned lump-sum to households). There is a slight decline in utility (less than 2 percent) due to the distortionary shifts in consumption among goods and leisure.

From society's perspective, the value of a unit of exogenous income is essentially unchanged. But because households will ignore the lump-sum return of revenues (or the provision of public goods), the private value of income declines in direct relation to the portion of incremental income that is taxed away. By valuing income from this private

perspective rather than a social perspective, the marginal social damage no longer reflects society's value of environmental quality in terms of income.

When we look at the values for MPD, we see large variations in that measure of marginal damage both across revenue levels and for different types of externalities. Indeed, for these scenarios where the optimal environmental tax rises with regularity across externality types and revenue levels, we observe MPD to be rising by more than 50 percent for the amenity externality, declining by 10 percent for the productivity externality, and varying only slightly from the optimal tax in the case of the income externality. On closer examination, we see that these variations are primarily due to the decline in the value of λ relative to α as rising tax rates imply that a unit of income is only partially allocated to private consumption, with the other portion being allocated to public revenues. In the case of the amenity externality, this phenomenon appears to explain the sharp rise in MPD. For the other types of externalities, we also observe a decline in the sum of private marginal damages (in utility units) relative to social damages. This is because these two types of externalities have direct effects on taxable income, and a portion of the losses are therefore revenue losses not private losses.[7]

In the cases of the income and productivity externalities, Parry and Bento (2002) and Williams (2002) conclude that the optimal environmental tax remains equal to the Pigovian rate, and they argue that this is because a "benefit-side tax interaction effect" exactly offsets the "cost-side tax interaction effect." In these cases, however, they are defining marginal damage differently than they and others have done for the amenity externality case. Marginal environmental damage is being defined for the income and

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[7] For the income and productivity externalities, Parry and Bento (2002) and Williams (2002) conclude that the optimal environmental tax remains equal to MPD. In their definitions of MPD, however, they omit the third term from the numerator of MSD and the second and third terms from its denominator.

productivity externalities in terms of the gross change in income, without identifying how it is allocated between private consumption versus changes in public revenues. There would appear to be an inconsistency in this approach: when a change in income is due to environmental damage, the full unit of income is being recognized, but when valuing an exogenous change in income, only the change in private consumption is being recognized. Moreover, since the marginal damage is defined without considering how it will be allocated, the feedback effects on environmental quality is ignored (the third term in the numerator of (23p, 23y)). If this term is added to their measure of marginal damage in utility units, while still using λ as the numeraire unit of income, the relationship between this measure and the optimal environmental tax is identical to the relationship between τ^* and MPD in the amenity case.[8]

D. Discussion

Our theoretical expressions for optimal environmental taxes would be of little practical use without an estimable benchmark or standard against which policy objectives could be set and judged. Moreover, recent debate in the theoretical literature has relied heavily on comparisons of the optimal environmental tax and marginal private damages to make predictions about the benefits and costs of environmental policies, and changes in the levels of government revenues. For the two benchmarks considered above, the following observations are offered in regard to possible criteria.

First, does the benchmark have a theoretical basis for judging whether the welfare gains from environmental taxation with revenue recycling are higher or lower than marginal

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[8] This result can be anticipated by examining (24). We can substitute λ/λ for α/α to see that if the complete numerator from MSD, $\phi e'$, is used for all types of externalities, then the relationship between τ^* and $\phi'e/\lambda$ will be invariant across types of externalities.

social damages at a tax rate equal to MSD? The first-order conditions of the optimal tax problem includes $\phi e'$, plus other expressions pertaining to the private and social costs of taxation. If we define MSD using α as a numeraire, then we have maintained in these first-order conditions an expression which is equal to the Pigouvian rate. And if we then find that the optimum is reached at t*<MSD, we can assume that other welfare changes represented in those first-order conditions offset the gains from reducing pollution short of the point where the optimal environmental tax equaled marginal social damage. The evidence presented above suggests the opposite, that at τ*=MSD, the net benefits from environmental taxation continued to justify further increases in τ to a point about 50 percent above MSD.

By contrast, if we introduce λ as a numeraire in these first-order conditions, we will have an expression for marginal damages with a socially valued numerator ($\phi e'$) and a privately valued denominator (λ). It becomes difficult to justify ignoring the two terms which cancel out at the first-best optimum in the denominator (as in (9)), while including two similar terms in the numerator. Whereas MSD does indeed reflect the social marginal rate of substitution between the environment and income, MPD does not reflect social valuations as a general proposition, nor do components of MPD emerge from the first-order conditions of the model, except as an expression which is equal to the optimal tax at the first-best optimum. The evidence presented above indicates that wide differences in τ*/MPD do not correspond to differences in the welfare changes from revenue-motivated taxation or environmental tax reform. Moreover, the definitions of marginal damages used in the recent literature for the income and productivity cases raise additional

questions of consistency across types of externalities and the theoretical justification behind the definitions being used.

 Second, does the benchmark provide a basis for setting policy given the practical difficulties of empirical measurement? Although it may be the case that elements in the numerator and denominator of MSD add complications compared to estimating MPD, the optimal tax is ultimately a function of MSD, as evidenced by the single expression for τ^* which applies to all types of externalities. All the elements of MSD, μ, and α must be estimated to arrive at τ^*. Estimating MPD may be a simpler way to obtain a measure of damages in the amenity case, but this simply shifts the complications to an exercise in estimating how τ^* will diverge from MDP, which will depend on the type of externality and the differences between private and social values of income. Whereas τ^* is defined here succinctly in (24), the alternatives using MPD would appear to involve many more terms to evaluate the sources of divergence between τ^* and MPD (see, for example, Williams 2002, p. 266).

One may point to a number of reasons for preferring one measure of marginal damages over another, such as the ease of empirical measurement, or whether the economics profession is more accustomed to using one versus another. For present purposes of confirming or refuting predictions about the second-best welfare changes associated with environmental policy, however, there should be no dispute that the validity of the predictions should be the basis for using one approach over another.

V. Concluding comments

In the past few years the economic justification for environmental policy has been called into question by a theoretical literature relying on comparisons between the optimal environmental tax in a second-best setting and a benchmark measure of the Pigouvian rate, the sum of marginal private damages. Although this benchmark expression reflects society's marginal rate of substitution between the environment and income at the first-best optimum, it does not reflect social valuations either in the absence of corrective taxes, or in the presence of revenue-motivated taxes. Indeed, the presence of revenue-motivated taxes causes private valuations to diverge significantly and inconsistently from social valuations across different types of externalities. These differences mainly reflect the fact that in a second-best setting, an incremental unit of income will be allocated in part to private consumption and in part to government either for the provision of public goods or, in these stylized models, to be returned to households in lump sum payments. As a result, the private value of income is an inverse function of the tax level, but this does not reflect a decline in the social value of exogenous income. Using this private value as a social numeraire distorts this measure of marginal environmental damages relative to its social value.

The relationship between the optimal environmental tax and MSD is consistent across all types of externalities, and it is stable to the extent that the model's functions are nearly linear over the relevant range, so that social marginal valuations are relatively unchanged. Comparisons between the optimal environmental tax and MSD are consistent with our intuition and the results anticipated with the double dividend hypothesis: the optimal environmental tax generally exceeds MSD when a "revenue-recycling effect" lowers the cost of environmental policy. In this regard, the results are highly consistent with the classical literature: environmental waste disposal services, like other goods, should be

priced according to their social cost in keeping with the Pigouvian Principle in a first-best setting, and in a second-best setting a Ramsey rule will generally add a tax premium on top of the Pigouvian rate.

Recent debate in the literature is reminiscent of Baumol (1972) concluding, "it is ironic that just at the moment when the Pigouvian tradition has some hope of acceptance in application it should find itself under a cloud in the theoretical literature." Although set in an earlier time, these sentiments seem valid again today. The implementation of large-scale emissions trading, congestion pricing, and discussions of national carbon taxes, has been juxtaposed with the suggestion that a heretofore unrecognized "tax interaction effect" castes doubt on the merits of pollution control policies, and implies that government's must choose between protection of the environment and financing expenditures on other public goods, but that doing more of one will raise the costs of doing the other.

One can, of course, compare optimal taxes to any kind of benchmark one wishes. The path taken recently, however, has led toward inconsistent and logically incongruous results across types of externalities, explanations that require the introduction of new distortionary phenomenon, newly defined measures of partial welfare changes called "gross cost," etc.. Most importantly, the predictions made based on the relative magnitude of optimal environmental taxes and this definition of marginal damages appear to reflect the inconsistency of the chosen benchmark rather than movement of the optimal tax in one direction or the other.

There is no doubt that both MSD and MPD can be shown to equal "the Pigouvian rate" at the first-best optimum, which raises ambiguity about which one should be used to make valid inferences and predictions about the benefits and costs of environmental policy in

second-best setting. There is no evidence, however, that the authors of the recent tax interaction literature recognized that there were two possible definitions of marginal damages, or that the choice of one versus the other could lead to valid versus invalid inferences and predictions. The critical distinction between the social and private marginal utility of income appears to have been simply overlooked.

The analysis performed here finds that it is not the optimal environmental tax that behaves unexpectedly, but rather the benchmark of marginal private damages, which is found to have no consistent relationship with marginal social damage (defined from society's perspective), the optimal environmental tax, or the welfare changes from revenue-neutral environmental tax reform. In sum, the traditions in optimal tax theory begun by Pigou and Ramsey, and advanced further by Sandmo, Diamond, Baumol and others, appear to need no fundamental revision.

Table 1. Numerical model results for optimal environmental taxation in first-best, second-best settings and for "green tax reform"													
Amenity externality	τ^*	MSD	$\dfrac{\tau^*}{MSD}$	α	ϕe'	t_n	μ	MPD	$\dfrac{\tau^*}{MPD}$	λ	$m\,\dfrac{dv}{dE}$	Welfare change from first-best ($ billions)	Welfare change for "green tax reform" ($ billions)
First-best optimum	25.4	25.4	1.00	0.39	10.0	0.00	0.39	25.4	1.00	0.39	10.0		
Second-best:													
G = $0.5 trillion	28.2	25.4	1.11	0.39	10.0	0.13	0.40	28.3	1.00	0.35	10.0		
G = $1 trillion	31.2	25.3	1.23	0.40	10.0	0.28	0.41	31.5	0.99	0.31	10.0		
G = $2 trillion	37.5	25.0	1.50	0.40	10.0	0.61	0.43	38.2	0.98	0.26	10.0	-$76.7 billion	1.44
												(-1.9 %)	
Income externality													
First-best optimum	25.4	25.4	1.00	0.39	10.0	0.00	0.39	25.4	1.00	0.39	10.0		
Second-best:													
G = $0.5 trillion	28.3	25.4	1.11	0.39	10.0	0.13	0.40	25.2	1.12	0.35	8.9		
G = $1 trillion	31.5	25.5	1.24	0.40	10.1	0.29	0.41	25.3	1.25	0.32	8.0		
G = $2 trillion	38.3	25.7	1.49	0.40	10.2	0.62	0.43	25.3	1.51	0.26	6.6	-$77.2 billion	1.51
												(-1.9%)	
Productivity externality													
First-best optimum	25.4	25.4	1.00	0.39	10.0	0.00	0.39	25.4	1.00	0.39	10.0		
Second-best:													
G = $0.5 trillion	28.3	25.4	1.11	0.39	10.0	0.13	0.40	24.6	1.15	0.35	8.7		
G = $1 trillion	31.5	25.5	1.24	0.39	10.1	0.28	0.41	24.1	1.31	0.32	7.6		
G = $2 trillion	38.6	25.7	1.50	0.40	10.3	0.61	0.43	22.8	1.69	0.26	6.0	-$76.6 billion	1.52
												(-1.9%)	

Notes: Green tax reform compares welfare under uniform taxation with optimal taxation for a given revenue requirement.

Values for τ^*, MSD, MPD, ϕe', and $m\,(dv/dE)$ are in dollars per ton.

Tax levels at G = $2 trillion are equivalent to a marginal income tax of 38 percent.

Appendix A: Derivations of second-best optimal taxes

Optimal tax expressions are derived below for three types of externalities based on general models with n+1 goods. The general approach is similar to Sandmo (1975).

Amenity externality

For the case of an amenity externality, the problem can be formulated as one in which m identical individuals maximize utility $U = u(x_0, x_1, x_2, ..., x_Z, ..., x_n, E)$ for goods $j = 0, ...,$ n, where leisure is x_0 and where labor supply is taken out of a time endowment, y, so that labor supply, $l=y-x_0$. Units are chosen for goods and income so that all pre-tax prices equal one, and where there are n-1 non-polluting x goods (excluding leisure) and one good x_z which produces an environmental externality. The consumption of x_z is assumed to erode the environment, E, where $E = e(mx_z)$ and where $de/d(mx_z) < 0$.

In the amenity case, labor productivity, h, is constant, so that aggregate output is defined as $m(y-x_0)h = \Sigma mx_i$. Transfers of mg are financed by distortionary taxes, and E enters the utility function directly. Each household's maximization problem can be stated as

$$\underset{x_0 \ldots x_n}{Max}: \quad u(x_0, x_1, \ldots x_n, E)$$

$$s.t. \quad (y - x_0)h + g = \sum_{j=1}^{n} (1 + t_j)x_j$$

The Lagrangian expression for each household taking E and g as given is thus

$$= u(x_0, x_1, \ldots x_n, E) + \lambda \left[(y - x_0)h + g - \sum_{j=1}(1+t_j)x_j \right] \text{ for } j = 1, \ldots, z, \ldots, n.$$

[A1]

Consumer prices are given as $p_j = 1 + t_j$ for $j = 1$ to n, but where income is untaxed, so that $p_0 = 1$.

The first-order conditions for each household take the form

$$U_j = \lambda(1 + t_j) \qquad\qquad\qquad\qquad\qquad\qquad j = 1, \ldots, n$$

$$U_o = \lambda h$$

$j = x_0$.

Our social optimization problem can be stated as

$$Max_{t_1 \ldots t_n} : \quad m\left[u(x_0, x_1, \ldots x_n, E) \ \ s.t. \ \ (y - x_0)h + g = \sum_{j=1}^{n}(1 + t_j)x_j\right]$$

$$s.t. \qquad m\sum_{j=1}^{n} t_j x_j = mg$$

$$E = e(mx_z)$$

[A2]

Taking the dual approach, we define the household's indirect utility function as $v(p_0$ $,p_1, \ldots p_n, y, g, E) = u(x_1*(p_0, p_1, \ldots p_n, y, g, E), x_2*(p_0, p_1, \ldots p_n, y, g, E), \ldots x_n*(p_0, p_1, \ldots p_n, y, g, E)$,

so we can state the social optimization problem as the Lagrangian equation

$$= mv(p_0, p_1, \ldots p_n, y, g, E) + \mu\left[m\sum_{j=1}^{n} t_j x_j - mg\right] + \phi\left[e(mx_z) - E\right].$$

The first-order conditions are

$$-\lambda x_j + \mu\left[\sum_i t_i \frac{\partial x_i}{\partial p_j} + x_j\right] + \phi^a e' \frac{\partial x_z}{\partial p_j} = 0 \quad \forall \ j \neq 0 \cdot$$

[A3]

from which the term related to environmental damage in this expression, succinctly

denoted as $\phi^a e'$, can be expressed as

$$\phi^a e' = -m\left[\frac{\partial U}{\partial E} + \mu \sum_i t_i \frac{\partial x_i}{\partial E} + \phi e' \frac{\partial x_z}{\partial E}\right] e'.$$

[A4]

From this expression we can see that the environmental component involves marginal

social damage in utility units which includes the direct loss to households, the loss of

revenues due to changes in consumption, and indirect losses to households from the

environmental consequences of changes in consumption of the polluting good.[9]

Derivations of optimal tax rules often include substitution of the Slutsky equation in such

a way that the social marginal utility of income, α, is represented along with the shadow cost of

raising an additional dollar of revenue (Auerbach 1985). Diverging slightly from the approach

taken by Sandmo, we rearrange the planner's first-order conditions and use the Slutsky equation

to split the cross-price effects into compensated effects (superscript U) and effects on income, y,

as $\quad \dfrac{\partial x_z}{\partial p_i} = \dfrac{\partial x_z^U}{\partial p_i} - x_i \dfrac{\partial x_z}{\partial y}$. We substitute α to obtain

$$-\alpha x_j + \mu \sum_i t_i \frac{\partial x_i^U}{\partial p_j} + \mu x_j + \phi^a e'\left(\frac{\partial x_z^U}{\partial p_j} - x_j \frac{\partial x_z}{\partial y}\right) = 0 \qquad \forall\, j \neq 0.$$

[A5]

where for our n good model, the social marginal utility of income is expressed as

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[9] Sandmo does not explicitly consider the effect of changes in environmental quality on demands for goods, so the second and third terms on the right-hand side of [A14] is omitted in his analysis. However, given the highly stylized representation of an environmental externality, one may assume that Sandmo has assumed the effects to be incorporated as indirect components of the cross-price effects with respect to the polluting good.

$$\alpha = \lambda + \mu \sum_{i=1}^{n} t_i \frac{\partial x_i}{\partial y} + \phi e' \frac{\partial x_z}{\partial y}.$$

We define $\check{\mathbf{S}}$ as the determinant of the Slutsky matrix of compensated demands, so that $\mathbf{S_{ij}}$ is the cofactor of the element for the *jth* row (price) and *ith* column (quantity). Using Cramer's rule we can solve for the optimal taxes

$$t_j = \frac{(\mu - \alpha)}{\mu} \frac{\sum_{i=1}^{n} x_i S_{ij}}{\check{S}} - \frac{\phi^a e'}{\mu} \frac{\sum_{i=1}^{n} \left(\frac{\partial x_z^U}{\partial p_i} - x_i \frac{\partial x_z}{\partial y} \right) S_{ij}}{\check{S}}$$

[A6]

where the second term on the right-hand side is the environmental component of the tax. From theorems about the expansion of determinants, we know that

$$\sum_{i=1}^{n} \frac{\partial x_z^U}{\partial p_i} S_{ij} = \begin{cases} 0 & \text{for } j \neq z \\ \check{S} & \text{for } j = z \end{cases}.$$

Let R denote the "Ramsey term" for compensated demands or $R \equiv \dfrac{\sum_{i=1}^{n} x_i S_{ij}}{p_j \check{S}}$ reflecting the revenue generating potential for a marginal change in the tax on x_i due to the direct and indirect effects on consumption for all goods. Further simplify the notation by defining the income effect on the environment as $\sigma^a = \phi^a \sum_{i=1}^{n} x_i \frac{\partial x_z}{\partial y}$. We can thus rearrange terms and simplify so that the optimal tax expressions can then be written as

$$\frac{t_j}{(1 + t_j)} = \frac{(\mu - \alpha + \sigma^a)}{\mu} R \qquad \forall j \neq z$$

[A7]

and

$$\frac{t_j}{(1+t_j)} = \frac{(\mu - \alpha + \sigma^a)}{\mu}R - \frac{\phi^a e'}{\mu(1+t_j)} \qquad j = z$$

[A8]

These implicit solutions are difficult to interpret by inspection, in part because of the lack

of transparency in interpreting **R**. Moreover, although the environmental component of

the tax in [A8] appears to be separable from the standard formula, the independence is

illusory both because of the denominator $(1 +t_z)$ is endogenous and because the actual

level of the externality depends on the actual equilibrium and hence the optimal tax rates;

the same is true in the other direction (Sandmo 1975, Auerbach 1985).

The results differ from the expressions obtained by Sandmo involving uncompensated

demands. Sandmo concluded that the environmental damages of x_z "does not enter the

tax formulas for the other commodities, regardless of the pattern of complementarity and

substitutability" (1975, p. 92). In this alternative derivation, we see that the numerator in

the first term on the right-hand side includes σ, a term involving ϕ^a, indicating that the

presence of an externality raises the optimal tax on all goods due to their income effect:

by reducing real income, all taxes discourage consumption of the externality-producing

good to some extent, and these optimal tax rates will be higher as a result. These two

versions of the optimal tax results are not in conflict: in the model involving ordinary

demands, the income effects are implicit.

 In the sections below, optimal tax expressions are also derived for two other types of

externalities, productivity externalities and income externalities. The resulting optimal

tax expressions differ only in terms of the definition of marginal social damage, ϕ.

We are interested in the environmental component of the optimal tax on x_Z which can be

taken as the differential between the optimal tax on x_z and the optimal tax on good x_j, or

$\tau^* = t_Z^* - t_j^*$.

From the [A7] and [A8] we can express t_z^* as

$$t^*_z = \frac{\left(1 - \dfrac{\alpha + \sigma}{\mu}\right) R}{\left(1 - \left(1 - \dfrac{\alpha + \sigma}{\mu}\right) R\right)} - \frac{\alpha}{\mu\left(1 - \left(1 - \dfrac{\alpha + \sigma}{\mu}\right) R\right)} \frac{\phi e'}{\alpha}$$

[A9]

where from [A7} we can express the Ramsey term as

$$R = \frac{\dfrac{t^*_j}{(1 + t^*_j)}}{\left(1 - \dfrac{\alpha + \sigma}{\mu}\right)}$$

[A10]

To evaluate the optimal tax t^*_z relative to MSD, we substitute [A10] into the second term

of [A9] and rearrange to get

$$t_z^* = \frac{\left(1 - \dfrac{\alpha + \sigma}{\mu}\right) R}{\left(1 - \left(1 - \dfrac{\alpha + \sigma}{\mu}\right) R\right)} - \frac{\alpha\left(1 + t_j\right)}{\mu}\left[\frac{\phi e'}{\alpha}\right].$$

[A11]

We can evaluate the environmental component of the tax on x_z by evaluating the second

term in [A11], or

$$\tau *_z = \frac{\alpha\left(1 + t_j\right)}{\mu}\left[\frac{-\phi e'}{\alpha}\right]$$

where the term in brackets is MSD. Note that while the terms α in numerator and denominator could be replaced with λ, so that the optimal tax expression could involve the private marginal utility of income, the numerator involves ϕ rather than mU_z, so that the expression cannot be based on the sum of marginal private damages unless restrictions on preferences are assumed so that the second and third terms in ϕ can be dropped.

Productivity externality

We now consider a model where, rather than affecting utility directly, environmental quality affects labor productivity. Given the similarities with the derivation above, not all steps are repeated here.

In this model, labor productivity, h, is a function of environmental quality such that $h = h(E)$ where $E=e(mx_z)$. We define aggregate output as $m(y-x_0)h= \Sigma mx_i$, and where mg is financed through collection of tax revenues. Our maximization problem becomes

$$\underset{X_0 \dots X_n}{Max}: \quad u(x_0, x_1, \dots x_n)$$

$$s.t. \quad (y - x_0)h(E) + g = \sum_{j=1}^{n}(1 + t_j)x_j$$

[A12]

so that individuals maximize utility subject to their budget constraint while ignoring both the environmental consequences of their own consumption choices and government behavior. The Lagrangian expression for each household is thus

$$= u(x_0,x_1,...x_n) + \lambda \left[(y-x_0)h(E) + g - \sum_{j=1}(1+t_j)x_j \right] \text{ for } j = 1, .., z,...,n. \qquad [A13]$$

The social problem is then

$$\underset{t_1...t_n}{Max}: \quad m \left[u(x_0,x_1,...x_n) \ s.t. \ (y-x_0)h(E) + g = \sum_{j=1}^{n}(1+t_j)x_j \right]$$

$$s.t. \qquad m\sum_{j=1}^{n} t_j x_j = mg$$

$$E = e(mx_z)$$

[A14]

As above, the dual approach gives us the household's indirect utility function so we can

state the social optimization problem as the Lagrangian equation

$$= mv(p_0, p_1,...p_n, y, g, E) + \mu \left[m\sum_{j=1}^{n} t_j x_j - mg \right] + \phi \left[e(mx_z) - E \right] \qquad [A15]$$

In the presence of environmental effects on labor productivity, the first-order conditions

for the social optimization problem are

$$-\lambda x_j + \mu \left[\sum_{i=1}^{n} t_i \frac{\partial x_i}{\partial p_j} + x_j \right] + \phi e' \frac{\partial x_z}{\partial p_j} = 0 \qquad \forall \ j \neq 0$$

[A16]

where $\lambda = dV/dh = \partial U*/\partial h$ is the household's marginal utility of income. Let $\phi^P e'$

denote marginal social damages in utility units for the productivity externality case, or

$$\phi^P e' = m\left(\lambda(y-x_0) + \mu \sum_{i=1}^{n} t_i \frac{\partial x_i}{\partial h} - \phi e' \frac{\partial x_z}{\partial h} \right) h' e'$$

[A17]

Once again the marginal social damage includes the direct loss of income to households, the loss in revenues due to changes in consumption, and the indirect changes from the environmental consequences of changes in consumption of the polluting good.
 The derivation of the optimal taxes proceeds from this point as indicated above. The optimal tax expressions are similar and can be written as

$$\frac{t_j}{(1+t_j)} = \frac{(\mu - \alpha + \sigma^p)}{\mu} R \qquad \forall j \neq z$$

[A18]

and

$$\frac{t_j}{(1+t_j)} = \frac{(\mu - \alpha + \sigma^p)}{\mu} R - \frac{\theta^p e'}{\mu(1+t_j)} \qquad j = z$$

[A19]

Income externality

We now consider a model where the quantity of income is a direct function of the environment. In our stylized model, y, the time endowment, is made a function of E such that $y = y(E)$ where $E = e(mx_z)$. We define aggregate output as $m(y(E)-x_0)h = \Sigma mx_i$, and where mg is financed through collection of tax revenues. Each household's maximization problem can be stated as

$$\underset{X_0\ldots X_n}{Max}: \quad u(x_0, x_1, \ldots x_n)$$

$$s.t. \quad (y(E) - x_0)h + g = \sum_{j=1}^{n}(1 + t_j)x_j$$

[A20]

so that individuals maximize utility subject to their budget constraint while ignoring both

the environmental consequences of their own consumption choices and government

behavior. The Lagrangian expression for each household in this case is

$$= u(x_0, x_1, \ldots x_n) + \lambda\left[(y(E) - x_0)h + g - \sum_{j=1}(1 + t_j)x_j\right] \text{ for } j = 1, \ldots, z, \ldots, n. \quad\quad \text{[A21]}$$

And the social problem is then

$$\underset{t_1 \ldots t_n}{Max}: \quad m\left[u(x_0, x_1, \ldots x_n) \;\; s.t. \;\; (y(E) - x_0)h + g = \sum_{j=1}^{n}(1 + t_j)x_j\right]$$

$$s.t. \quad\quad m\sum_{j=1}^{n} t_j x_j = mg$$

$$E = e(mx_z)$$

[A22]

As above, the dual approach gives us the household's indirect utility function as *v(p0*

,p1,... pn, y,g,E) = u(x1*(p0 ,p1,... pn,y,g,E), x2*(p0 ,p1,... pn,y,g,E),... Xn*(p0 ,p1,...

pn,y,g,E), so we can state the social optimization problem as the Lagrangian equation

$$= mv(p_0, p_1, \ldots p_n, y, g, E) + \mu\left[m\sum_{j=1}^{n} t_j x_j - mg\right] + \phi\left[e(mx_z) - E\right]$$

In the presence of environmental effects on labor productivity, the first-order conditions

for the social optimization problem are

$$- \lambda x_j + \mu \left[\sum_{i=1}^{n} t_i \frac{\partial x_i}{\partial p_j} + x_j \right] + \phi^y e' \frac{\partial x_z}{\partial p_j} = 0 \qquad \forall \ j \neq 0$$

[A23]

where $\lambda = \dfrac{dV}{d(yh)} = \dfrac{\partial U^*}{\partial(yh)}$ is the household's marginal utility of income. Let

ϕ^R denote marginal social damages in utility units for the resource externality case, or

$$\phi^y e' = m \left(\lambda h + \mu \sum_{i=1}^{n} t_i \frac{\partial x_i}{\partial y} + \phi^y e' \frac{\partial x_z}{\partial y} \right) y' e'$$

[A24]

where marginal social damage includes the direct loss of income to households, the loss

in revenues due to changes in labor supply, and the indirect or secondary effect on

environmental quality.

The resulting optimal tax expressions are nearly identical to those above, or

$$\frac{t_j}{(1 + t_j)} = \frac{\left(\mu - \alpha + \sigma^y \right)}{\mu} R \qquad \forall j \neq z$$

[A25]

and

$$\frac{t_j}{(1 + t_j)} = \frac{\left(\mu - \alpha + \sigma^y \right)}{\mu} R - \frac{\phi^y e'}{\mu(1 + t_j)} \qquad j = z$$

[A26]

For all three types of externalities we obtain similar optimal tax expressions which differ

only in terms of the expression for marginal social damage expressed in utility units, ϕ. It

is worth noting that ϕ will differ from the sum of marginal private damages (in utility

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units) for each type of externality except for special cases involving restrictions on

preferences and parameter values.

APPENDIX B: Specification of the numerical climate-economy model

The numerical models representing the US economy include a primary CES utility function, $u=U(x,l)$ given as

$$U = \left(\gamma x^{-\rho} + (1-\gamma)l^{-\rho} \right)^{-1/\rho},$$
[B1]

and a secondary CES production function defining substitutions between f and n in $x=X(f,n)$ as

$$x = \left(\beta f^{-\delta} + (1-\beta)n^{-\delta} \right)^{-1/\delta}.$$
[B2]

This production function is a single CES function rather than the more disaggregated, nested CES structure of production in the Parry, Williams and Goulder model (1999). The functions and parameters have been calibrated to correspond to the second-best marginal abatement cost function from Parry, Williams and Goulder (1999).

Setting $\delta = -0.5$ implies that the elasticity of substitution between carbon emitting and non-carbon emitting consumption, σ_{nf}, equals $(1/1+\delta) = 2.0$. The value of $\rho = -0.167$, so that the elasticity of substitution between consumption and leisure, σ_{xl}, equals $(1/1+\rho) = 1.2$. In addition, $\gamma = 0.836$, $\beta = 0.667$, and $m=1$.

For the productivity externality, other than the constraints emerging directly from the household first-order conditions, we have the budget constraint

$$(1+t_f)f + (1+t_n)n = (y^0 - l)[1 + r(q-E)] + G$$
[B3]

where $Y^0 = 4,101,535$, $r=0.0000072$ and $q=1448$, and the environmental constraint, $E=\pi f$ where $\pi=.00225$.

In the case of the income externality, labor productivity is instead fixed at $h=1$ and y is a function of but we have

$$(1+t_f)f + (1+t_n)n = \left[(y^0 + w - sE) - l)\right] + G \qquad \text{[B4]}$$

where $Y^0 = 4,101,535$, $w=1449$, $s=25.44$. For this model, carbon content is slightly higher in $E=\pi f$ where $\pi = .002272$.

In the case of the amenity externality the budget constraint is simplified since y is fixed at y^0 and $h=1$, so that

$$(1+t_f)f + (1+t_n)n = (y^0 - l) + G. \qquad \text{[B5]}$$

The utility function, however, includes an additional term making environmental quality separable, or

$$U^A = \left(\gamma x^{-\rho} + (1-\gamma)l^{-\rho}\right)^{-1/\rho} + k(q-E) \qquad \text{[B6]}$$

where $k=10$ and $q=1546$. The pollution coefficient, $\pi = 0.00225$.

All three models produce a first-best optimum where the carbon tax is \$25.4 per ton, and both MSD and MPD are also 25.4. The social, as well as the private, marginal utility of income is 0.39 at this optimum. Similarly, both the social and the private marginal damage in utility units equals 10. There are slight differences in household allocation between goods and leisure at the first-best optimum.

At the second-best optima where revenues and tax rates are similar to the U.S. economy (at G=\$2 trillion), the uncompensated labor supply elasticity for each model is in the range of estimates for the U.S. economy ($\cong 0.15$).

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Comments on Carbon Taxes and Trades
EPA Conference on Market Mechanisms
and Incentives for Environmental Management, May 1-2,2003

By Roberton C. Williams III
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Introduction

The literature on environmental policy with pre-existing distortionary taxes addresses two important policy questions. First, how do pre-existing distortionary taxes affect the choice among different regulatory instruments: taxes, tradable permits, or various types of command-and-control? Second, how do pre-existing taxes affect the optimal degree of regulation? Each of the three papers in this session addresses some aspect of one or both of these questions.

I will begin with a very brief review of the important theoretical concepts from the prior literature on environmental policy with pre-existing taxes. I will then go on to comment specifically on each of the three papers presented in this session. Finally, I will return to the two policy questions I just mentioned, and attempt to draw some conclusions for policy based on the three papers.

The prior literature has identified two welfare effects that arise in the presence of pre-existing distortionary taxes. The first is the revenue-recycling effect: revenue raised by an environmental policy can be used to cut pre-existing distortionary taxes, producing a welfare gain. But this is offset by the tax-interaction effect: environmental regulation drives up the cost of production, thus reducing the real return to factors of production (ie, capital and labor), discouraging supply of these factors, thus exacerbating the pre-existing distortions in those factor markets and producing a welfare loss. The recent book edited by Larry Goulder (2002) provides a collection of the important papers from this literature.

Comments on the paper by Ian Parry

This paper provides a non-technical summary of several papers by Ian Parry (with a variety of co-authors, including myself). It addresses both of the policy questions mentioned earlier. On the issue of instrument choice, it points out that policies that raise revenue, such as a pollution tax or auctioned emissions permits, can generate a revenue-recycling effect. This gives such policies an important advantage over other regulatory instruments, such as grandfathered emissions permits, which do not generate revenue.

On the question of the optimal degree of regulation, the paper points out that the tax-interaction effect will typically exceed the revenue-recycling effect, thus implying that environmental regulation should be less stringent than it would be in the absence of pre-existing taxes. The intuition for this point is relatively simple; ignoring environmental considerations, broad-based factor taxes are generally more efficient means of raising revenue than are relatively narrow-based environmental taxes.

But, while this will be true for the typical case, that does not mean it will always be true. If the pre-existing tax system is suboptimal, and if the environmental tax offsets that, then pre-existing distortionary taxes may increase the optimal level of environmental regulation. In one example Parry cites, the US income tax favors certain kinds of consumption: medical care, owner-occupied housing, etc. If there is no legitimate reason for such preferences, then environmental taxes (which do tax such consumption) may well be more efficient–even on purely non-environmental grounds–than the income tax. Thus, the optimal level of an environmental tax could exceed marginal environmental damage.

I have no significant criticisms or suggestions for how to improve this work, both because it is based on research already published in good peer-reviewed journals, and because I was a co-author of several of the those papers. Therefore I will proceed on to the other two papers, which describe newer work.

Comments on the paper by Richard Howarth

Howarth's paper looks at optimal carbon taxation, using a simple dynamic computational general equilibrium model of the world economy. It makes two key points. First, the optimal carbon tax (and the welfare gain from implementing that tax) varies substantially based on how the tax revenues are used; using the revenue to cut capital taxes leads to a higher optimal carbon tax and larger welfare gain than if the revenue is used to cut labor taxes (which in turn yields a higher optimal tax than if the revenue is returned lump-sum). Second, pre-existing taxes on capital imply that the appropriate discount rate will generally differ from the marginal product of capital (which would be the appropriate rate in a first-best world). For a stock externality such as global climate change, where emissions today cause damage in the future, the discount rate plays an important role in determining optimal policy. The first point is not new–papers by Bovenberg, Goulder, and others have made this observation before. However, the second point– on the discount rate–is new, at least for this literature (the literature on discounting has been aware of this issue for a long time). Thus, I will focus my comments on this second point.

The point is relatively simple. Taxes on capital cause the after-tax rate of return on capital to be less than the pre-tax return. In this case, it is difficult to determine which rate to use as the discount rate; indeed, the discounting literature has shown that the appropriate rate will generally not be equal to either the pre-tax or after-tax rate of return. And for a long-lived

pollutant such as carbon, even small changes in the discount rate can produce large changes in the present discounted value of a given stream of future damages. The prior literature has tended to focus on the cost side–typically assuming a particular value for discounted damages, rather than modeling damages explicitly–and thus has generally ignored this issue.

However, it is difficult to discern the importance of this issue from Howarth's current results. The second-best optimal carbon tax will differ from the first-best optimal tax for two reasons. First, as noted by the prior literature, the combination of revenue-recycling and tax-interaction effects implies that the second-best optimal tax will not equal discounted damages. Second, differences in the appropriate discount rate between the first-best and second-best imply that discounted damages will differ. Howarth's paper presents the first-best and second-best optimal tax rates, but does not distinguish how much of the difference between those rates is due to each of these two reasons.

It would be relatively easy to distinguish these two effects by comparing the results to those for the case of a flow pollutant–one for which emissions in a given time period cause damage only in that period. In such a case, the discount rate will not matter, which will make it possible to isolate the influence of the revenue-recycling and tax-interaction effects in Howarth's model. I would suggest that he introduce a flow pollutant into the model, and calibrate the marginal damage from the pollutant such that the optimal tax rate on the flow pollutant is equal to the optimal carbon tax in each period (which will generally require marginal damages to differ across periods). The marginal damage from the flow pollutant will then equal the discounted marginal damage from carbon emissions, making it straightforward to calculate the appropriate discount rate. I suspect that this will show that the divergence in discount rates between the first-

best and second-best plays a significant role in determining the optimal carbon tax, but very little role in determining how that optimal tax varies based on how the revenue is used.

Comments on the paper by William Jaeger

This paper proposes a new definition for marginal damage in the presence of pre-existing distortionary taxes. It then notes that under this definition, there is a consistent relationship between marginal damages and the optimal tax across different externality types, and that the optimal pollution tax exceeds marginal damage. The paper also claims that under this definition of marginal damage, there is no tax interaction effect. The first two points strike me as correct–though I would disagree about the interpretation and the practical relevance of these points–while the third strikes me as likely to be incorrect.

The paper defines marginal damage as the ratio of the Lagrangian multiplier on environmental quality in the social planner's problem to the Lagrangian multiplier on gross income–or, more intuitively, as the social planner's marginal willingness to pay for improved environmental quality. This definition has the advantage that it is the same regardless of the type of externality, and that it yields the same relationship between marginal damage and the optimal tax.

In contrast, one of my recent papers (Williams, 2002) uses three different definitions of marginal damage for three different externality types. For an externality that directly affects utility, it defined marginal damage as the sum of individuals' willingness to pay. For an externality affecting productivity, it defined marginal damage as the value of lost production. And for a health externality, it defined marginal damage as the cost of additional medical care

plus the value of time lost to illness. Furthermore, the relationship between the optimal tax and marginal damage is different for each type of externality.

Having three different definitions–and three different formulas for the optimal tax–may seem needlessly complex. But in practice, Jaeger's new definition isn't any simpler. The definitions I chose correspond to how environmental damage is measured empirically in each case. In contrast, Jaeger's new definition of damages cannot be directly measured in practice, and the relationship between his definition and empirical measures of marginal damage is different for each type of externality. Thus, the process of calculating the optimal tax from an empirical measure of damages is no simpler under his definition than under the definitions in my paper; it merely moves the complexity to a different step in the calculation.

Jaeger's new definition also implies that the optimal tax exceeds marginal damages, at least for typical parameter values. But one must be very careful in interpreting this result: it is not that his approach yields a higher optimal tax for a given economy than the prior literature would indicate, but rather that it yields a lower figure for marginal damage. The following example (drawn from Goodstein, 2003) makes it clear why the two approaches differ. Consider a case in which one unit of pollution leads to a 10 util reduction in utility, and the marginal utility of income is 6 utils/dollar. Under the prior literature's definition, marginal damages are $1.67 per unit (the 10 util marginal damage converted into dollars by dividing by the marginal utility of income). Jaeger's definition differs in that it converts utility to dollars based on the social marginal utility of income–which differs from the private marginal utility of income because an additional dollar of pre-tax income also yields tax revenue for the government. Thus, if the social marginal utility of income is 10 utils/dollar, marginal damages equal $1 (10 utils per unit of pollution divided by the social marginal utility of income) under his definition. If the optimal

pollution tax is $1.30 per unit, then the prior literature's definition implies that the tax is less than marginal damage ($1.30<$1.67), while Jaeger's definition implies that the tax exceeds marginal damage ($1.30>$1). But, for any given economy, both approaches yield exactly the same optimal pollution tax; the difference arises because the dollar figure for marginal damages differs between the two approaches.

The only way that one would get a different result for the optimal tax as a result of this paper is if one were to make a mistake and use an optimal tax formula based on one definition together with a measure of damages based on the other definition. For example, if one were to use an optimal tax formula based on Jaeger's definition of damages together with a figure for the marginal damage from a particular pollutant based on the prior literature's definition (which corresponds with most empirical measures of damage), the resulting "optimal" tax would in fact be much larger than the true optimal tax. Making the opposite mistake–combining the prior literature's formula for the optimal tax with a damage estimate based on Jaeger's definition– would yield too low a tax rate. Thus, while it strikes me that while this paper's results may be of theoretical interest, they have essentially no practical importance–as long as one does not make the mistake of using inconsistent definitions of marginal damage.

Finally, the paper suggests that under Jaeger's definition of marginal damage, there is no tax-interaction effect. I suspect that this is incorrect. What the paper has shown is that, under Jaeger's definition, the magnitude of the revenue-recycling effect exceeds that of the tax-interaction effect. That could imply that there is no tax-interaction effect under this definition, or it could imply that the tax interaction effect still exists, even under this definition, but is smaller than under the definition used by the prior literature. It would be relatively simple to check which explanation holds true. I would suggest modifying the model so that the pollution tax

revenue is returned lump-sum, rather than being used to cut the labor tax. This will eliminate the revenue-recycling effect. If the optimal tax equals marginal damage in this case, then that would imply that there is no tax-interaction effect. If, as I suspect will be the case, the optimal tax does not equal marginal damage, then that would indicate that there is a tax-interaction effect, even under Jaeger's definition of damages.

Conclusions

Based on these three papers, what can we conclude about the two policy questions I mentioned earlier? First, on the question of instrument choice, it is clear that emissions taxes or auctioned permits will be more efficient than grandfathered permits, as Ian Parry's paper noted. Recycling revenues to cut other taxes produces a welfare gain, and this is not possible under a system of grandfathered permits. Second, as noted by both Parry's and Howarth's papers, the more distortionary a pre-existing tax is, the larger the gain from recycling pollution tax revenues to reduce the rate of that pre-existing tax. Third, as pointed out by Howarth's paper, pre-existing taxes affect the discount rate, and this will have potentially important implications for the taxation of a stock pollutant. Finally, as Jaeger's paper makes clear, the definition of damages matters. One should be very careful not to use an optimal tax formula based on one definition together with an estimate of damages based on a different definition. However, as long as one does not make that mistake, Jaeger's approach yields the same optimal tax as does the prior literature.

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May 1, 2003 4:45 PM

Question and Discussion Session

Q. Alex Farrell, University of California at Berkeley,
This question relates to auction to permits only. In addition to the things you have talked about with these macro economic efficiencies, there are at least two effects that can probably be achieved with grandfathered permits to some degree. The first is the efficiency of the allowance market itself. The way this occurs is by reducing uncertainty. Uncertainty would be reduced by making it easier for new participants to enter, and also through the provision of both earlier information and reliable information on the price of allowances.   Participants in allowance markets are very concerned about the inability to obtain allowances at almost at any price in the future. An auction mechanism, even though it could be expensive, could reduce non-compliance. The second effect is an innovation effect which occurs from pricing all emissions more directly than a cap and trade program. Individuals have shown for an SO2 market, that if you have the ability to control emissions, not controlling them when the cost is actually lower than a current allowance price is money left on the table. These are two effects that might further improve the operation of the regulatory system given there are lots of second best activities.

A. Ian Perry
Point well taken. What we have been discussing has only been the static welfare effects of pollution control. Obviously in a broader analysis you would want to take into account impacts on induced innovation. Those are very important over time. Forty years from now what will matter is how much innovation we did to develop cleaner technologies in the transportation sector and electricity sector. It is very important when choosing amongst different policies to consider how they might have different effects on incentives to innovate.

A. Richard Howarth
I agree with that comment as well. I haven't done it yet, but something that I want to do actually with this model that I have been working with is to put in the technical changes and then see how having ITC in the dynamic model, like what I have, how that changes what a second best tax looks like.

Q.
This question is about permits in general whether auctioned or grandfathered. It's clear from the discussion that if you have a tax you have revenue and you have to dispose of the revenue and this is offset someplace with distortionary taxes elsewhere in the economy. If you auction off permits again you are also raising revenue. If you grandfather permits and let the market operate only within the private sector so that the revenue remains in the private sector, then revenue still needs to be disposed. In these circumstances, I have never heard anybody say 'How are the folks in the private sector, where the funds never leave, going to use their returns and sales and so on.' What are the efficiency effects and the income generating effects and how that might they be compared to the efficiency gains by revenue recycling?

A. Roberton Williams,

Essentially the key with recycling through tax cuts you is that you get both a substitution and an income effect. If you cut taxes or allow the private sector to retain the revenues you get income effects. Income effects are going to go the other direction, so labor and investment decrease, and current consumption increases. If you have pre-existing tax distortion, these effects are going to create a situation where you don't have enough savings, don't have enough investment, don't have enough labor supply. Income effects worsen those distortions. Substitution effects reduce those distortions. That's why those two effects are going to go in opposite directions.

Q. Skip Laitner, US EPA, Office of Atmospheric Programs
I want to build a question on the issue of second best. We've suggested that revenue recycling could have some benefits because of reducing distortionary effects of some pre existing taxes and taking advantage of the market mechanism. What if the market itself isn't all that efficient? I'll give you an example. I'll use the ethylene industry which produces a lot of basic goods for our economy. We might have one average plant in the ethylene industry that might use 8K Btu per pound of ethylene for example but a very bad plant might use 8K, 9K, 10K Btu, and a very good plant might use 6K. So if we are using a representative agent to capture the dynamic of an overage plant there is a huge disparity among the performance of individual firms within individual sectors. In fact a good bit of work suggests a lot of work and a lot of little inefficiencies at all levels whether things are technologically based or managerial based. So I am wondering how this discussion will emerge if we begin to think more in terms of an agent based representation of these issues rather than a representative agent. That might uncover other market efficiencies that might further amplify this kind of discussion.

A. Richard Howarth
I guess there are inefficiencies in energy market and there is slack. And there are a lot of cost effective energy efficient technologies which the market is not taking advantage of because of various market failures. Policy makers need to focus on both getting the prices right, which is what we are discussing here, and on finding ways to make markets work more efficiently at the prices they see. In some of these models I guess energy efficiency programs for example would increase the decarbonization rate of the economy in a model like mine. So I guess we haven't address that question in this set of talks but clearly that's also a part of the big picture.

A. Roberton Williams,
I think Dallas Burtraw has also done some work that has firm level heterogeneity including tax interactions with Matt Cannon.

A. Richard Howarth
Also in a theoretical plan, my impression is that evolutionary economics offer some tools that are useful in looking at questions of technology adoption. Although how ideas from that research get integrated with ideas from the policy optimization models that we talk about it is of course a big task although something that ultimately needs to be done.

Q. June Taylor, Journalist,

When talking about recycling the carbon tax revenues to reduce labor taxes, payroll taxes and income taxes seemed to be lumped together. I wanted to know if you have ever separated any of them out because income taxes are nominally progressive and payroll taxes are regressive. Payroll taxes are split by those who are paid by employer and those paid by us working folks. So how do you tease out the economic stimulus benefits of reducing labor taxes when labor taxes are different? Also, as you look at the long run how do you take into account the change in demographics and the decreasing labor supply we foresee in the industrialized countries?

A. Ian Perry
The models we have been dealing with are highly aggregated - they just take the labor market as a whole. It would be good in future work to disaggregate that labor market and break out different income groups who place different rates of income tax. The problem is we have pretty good estimates of how economy wide labor supply would respond to changes of average wage for the economy. As far as I know we don't have good estimates of how labor supply elasticity might differ across different income groups. It's not obvious because this labor supply captures the decision regarding how many workers with in the family are deciding to go into the labor force. It's capturing whether a spouse in a poor family verses a rich family is likely to be in the labor force or not. And it's capturing how much extra over time individuals are likely to work. It's not obvious necessarily whether high income families are more responsive in their labor supply decisions to changes in tax rates than low income families. But in principle that's a good point. I think that we should take a more careful look at this revenue recycling effect in an analysis that breaks out different income groups and tries to asses how people facing different tax rates would vary in their labor supply response. It might alter the results somewhat. That would be a good research agenda if we had some evidence of how good labor supply elasticity's differ across different income groups. As regards to payroll tax, it's standard in economics to assume it doesn't really matter whether the payroll tax is levied on workers or on firms. Because when the labor markets are competitive, the firms have to pay the tax and firms are competitive, they would just tend to off set that by lowering the nominal wage to compensate. It's a standard assumption in tax theory that it doesn't matter who bears the tax. If you abolish payroll taxes for workers then shift them on to firms then they would be roughly compensating wage adjustments that would offset that tax change so not much would really happen to labor supply. That's a conventional assumption that if labor markets are working well it doesn't really matter whether the taxes are levied on the worker or the firm you get the same result.

A. Roberton Williams,
I am doing work with Sarah West at Macalester College where we are actually trying to break out different households by income class, and look at both efficiency and distribution in a tax interaction model and get out some of the issues. Ian's right it's complicated and very much a work in progress.

Q. Richard Woodward, Texas A&M University,
I don't have a question but since it was sort of two on one I'd like to make sure Bill Jaeger has an opportunity to rebut.

A. William Jaeger,
Let me respond to a couple of things Rob Williams said. This is a complicated issue. He

indicated that I am coming up with a new definition of marginal damages. That sounds to me like suggesting that marginal damages were first defined in 1994. Peter Diamond talked about the social margin utility of income long before. It's not a new concept that the social margin utility of income is different than the private margin utility of income. I'm not creating new definitions. With different definitions we can say that one marginal utility is higher and one is lower. That is exactly my point. What's important in choosing a definition of marginal damages is that if you are going to make inferences by comparing the optimal tax to marginal damages, those inferences give you acute predictions about what's going on in terms benefits and costs and accurate predictions about what's going to happen if you raise the revenue requirement.